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ABSTRACT

Volume 1 contains all the invited papers accepted for the symposium. The subject matter covered in the papers includes physiological, anthropometrical, psychological, sociological, and economic human requirements and methods of evaluation; physical requirements and methods of evaluation in mechanical, acoustical, thermal, dimensional stability, compatibility, fire properties, and geometry areas; operation and maintenance requirements and methods of evaluation in such areas as maintenance, repair, replacement, and versatility; techniques and problems in applying the performance concept to design; and experience gained in application of the performance concept in design, building, and building use. (Author)

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Performance Concept in Buildings

Invited Papers

Joint
RILEM-ASTM-CIB
Symposium Proceedings

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Performance Concept in Buildings

Volume 1: Invited Papers

**Proceedings of a Symposium Jointly Sponsored by the International
Union of Testing and Research Laboratories for Materials and Structures (RILEM),
the American Society for Testing and Materials (ASTM), and the International
Council for Building Research Studies and Documentation (CIB)**

Philadelphia, Pa., May 2-5, 1972

Edited by

Bruce E. Foster: Secretary, Joint Symposium Committee

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Foreword

For well over fifty years the National Bureau of Standards has directed a substantial effort toward developing requirements and methods of test for buildings, components, and materials. The members of its staff have also participated in the work of both domestic and international technical committees dealing with these fields of activity, including committees of the three organizations sponsoring this symposium.

In recent years many of our research programs have emphasized the development of data and procedures needed for realization of the potential benefits promised by the formalized performance concept. Therefore, we welcome the opportunity to participate with colleagues throughout the world in the exchange of ideas and experience made possible by this Symposium. As a contribution to the Symposium, as evidence of our belief in the importance of its subject, and to make the information available to the building community, we are pleased to publish these Proceedings.

LEWIS M. BRANSCOMB
Director

Preface

The concept of a joint RILEM (International Union of Testing and Research Laboratories for Materials and Structures) and ASTM (American Society for Testing and Materials) symposium to be held in the United States was the subject of conversations extending over several years between representatives of these two organizations. As a result of several discussions, agreement was reached on holding a symposium on the Performance Concept in Buildings, a subject of great current interest throughout much of the world, and one of concern to both organizations. Since the Performance Concept is a subject of interest also to the International Council for Building Research Studies and Documentation (CIB), the CIB joined the other two organizations in sponsoring the symposium.

A steering committee was established consisting of Dr. R. C. Mielenz, Chairman, Master Builders Company of Cleveland, and the ASTM representative to RILEM; Professor Richard W. Bletzacker, Ohio State University, and Chairman of ASTM Committee E-6 on Performance of Building Constructions; Dr. J. R. Wright, National Bureau of Standards and the RILEM Delegate to the United States; and Mr. T. A. Marshall, Jr., Executive Secretary, ASTM. Upon his untimely death, Mr. Marshall was succeeded on the steering committee by Mr. W. T. Cavanaugh, ASTM Managing Director. The latter was often represented at planning meetings by Messrs. J. W. Caum and L. C. Gilbert. On occasion, the RILEM Secretariat was represented by Mr. M. Fickelson, Deputy Secretary of RILEM or by Dr. Wright, President of RILEM; while the CIB was represented by Mr. S. M. Charlesworth of the United States National Committee for CIB.

A Symposium Committee was formed which consisted of two members selected by each sponsoring organization. Membership consisted of Professor R. A. Jones, University of Illinois, Chairman, and Dr. Bruce E. Foster, National Bureau of Standards, Secretary, representing ASTM; Professor E. Amstutz, Zurich, and Mr. Tenho Sneck, the State Institute for Technical Research, Finland, representing RILEM; and Mr. Øivind Birkeland, Norwegian Building Research Institute, and Dr. Gérard Blachère, Centre Scientifique et Technique du Batiment, France, representing CIB.

Following solicitations of papers for the Symposium, a preliminary selection based on submitted abstracts was made by the Symposium Committee. Manuscripts tendered following this selection were submitted to a concentrated review during a two-day review session at the National Bureau of Standards. Some 60 staff members of the Building Research Division, assisted by four knowledgeable individuals representing the United States National Committee for CIB, participated in the review. The Symposium Committee took part in the review. It also held meetings devoted to final acceptance of papers, classification of papers by subject matter, and selection of rapporteurs.

The National Science Foundation, acting through the U. S. National Committee for CIB, made a substantial grant in support of the Symposium. As a contribution to the Symposium, and to make its findings available to the building community, the National Bureau of Standards agreed to publish the Proceedings.

Authors were requested to consider the reviewer's comments and submit final manuscripts in "camera-ready" form. Most of the abstracts, translated into French by a commercial concern, were reviewed for technical accuracy by Mr. M. Fickelson, Editor in Chief of the RILEM Bulletin. Time constraints prevented Mr. Fickelson from reviewing all the abstracts. Also, an attempt was made to correct obvious errors in the camera-ready copy. The contents of the papers are the sole responsibility of the individual authors. A table of factors for converting English units, and sometimes metric units, to S.I. units is included as an appendix.

The Proceedings is being issued in two volumes. Volume 1 consists of the invited papers, and will be available to Symposium authors and participants prior to the Symposium Meetings in Philadelphia, Pennsylvania, on May 2 - 5, 1972. Volume 2, which will be issued after the Symposium, will contain the opening statements by representatives of the sponsoring organizations, the keynote addresses, the opening paper on the history and scope of the performance concept, the reports of the rapporteurs, and hopefully, some record of the discussion during the Symposium sessions.

BRUCE FOSTER, Secretary
Sumposium Committee

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Abstract

Volume 1 contains all of the invited papers accepted for the Joint RILEM-ASTM-CIB Symposium on the Performance Concept in Buildings. Opening addresses and reports of the rapporteurs will be included in Volume 2. The Symposium was held in Philadelphia, Pennsylvania on May 2 - 5, 1972. The subject matter covered in the papers includes physiological, anthropometrical, psychological, sociological, and economic human requirements and methods of evaluation; physical requirements and methods of evaluation in mechanical, acoustical, thermal, dimensional stability, compatibility, fire properties, and geometry areas; operation and maintenance requirements and methods of evaluation in such areas as maintenance, repair, replacement, and versatility; techniques and problems in applying the performance concept to design; and experience gained in application of the performance concept in design, building, and building use.

Key words: Buildings; components; design procedures; experience in use; materials; performance evaluation; performance requirements; user requirements.

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

Design Specification - Operational Goals, Parameters, Synthesis, and Performance Criteria

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Evaluation, specification and monitoring in design has traditionally been based on the physical aspects of building environments. With a growing concern for human behavior there is a realization that the evaluation of environmental systems finally rests on whether the activities of people are satisfactorily supported by that system. Present methods of specification restrict the physical requirements in the interests of behavior but fail to note the design goals that are intended to be addressed. Further, the categorization of parameters, both physical and non-physical, tend to be isolated into problem areas rather than groups that can be correlated. Performance is also narrowly interpret ed in terms of physical entities alone.

A system is presented that co-ordinates environmental systems through a goal-parameter-synthesis-criterion specification which forms a base for design evaluation. The discussion includes the need for operational goals, a definition of non-physical parameters through an overt communication, a limiting stimulus system which links the organismic and environmental parameters, and criteria appropriate to the performance of operational goals. To illustrate the system certain lighting problems are studied from human behavior to light distribution. Rather than encouraging an attitude of regulatory compliance the system fosters alternative possibilities in design.

L'évaluation, la spécification et le contrôle d'un projet sont traditionnellement fondés sur les aspects physiques de l'environnement de la construction. Avec l'intérêt croissant qu'on attache au comportement humain, on en vient à admettre que l'évaluation des systèmes d'environnement repose sur le fait que les activités des gens sont entretenues ou non par ce système. Les méthodes actuelles de spécification limitent les exigences physiques au profit du comportement mais ignorent les objectifs fixés par le projet. En outre, la catégorisation des paramètres, tant physiques que non physiques, tend à les compartimenter au lieu de les répartir en groupes qui peuvent être mis en corrélation. La performance est du reste étroitement interprétée en termes d'entités physiques seulement.

Un système est présenté qui coordonne les systèmes d'environnement par une spécification: but-paramètre-synthèse-critère; qui constitue la base de l'évaluation. La discussion porte sur la nécessité de buts opérationnels, une définition de paramètres non physique par le moyen d'une relation manifeste, un système de stimulus limitatifs qui associe les paramètres appartenant à l'organisme vivant et au milieu, et les critères appropriés aux objectifs à atteindre. Pour illustrer le système, certains problèmes d'éclairage sont étudiés, depuis comportement humain jusqu'à la distribution de la lumière. Plutôt que d'encourager une attitude de conformité à la règle, le système multiplie les possibilités en regard du projet.

Key words: design evaluation; design specification; design synthesis; environmental systems; goal statements; parameter definition; performance criteria.

1. Problem areas

Design specification is vital to the rational evolution of our environment. It is a predictive statement of future activities and environmental features. From this predictive statement a projected evaluation can be made to ascertain the success or failure of such a venture. More broadly this becomes technology assessment. The specification should be capable of considering design problems for any detail, time of an event, and for any personality involved including promoters, designers, contractors, managers, monitoring agencies, and environmental occupants.

Materials oriented professionals will possibly charge that this form of specification is far too extensive for their concern. The salient point is that their problems are inherited from the broad context of a design and when their contribution is evaluated it is in terms of that design context. Disciplines of materials technologists must be consistent with those disciplines that embrace it. Our situation is that professions are "doing their own thing" rather than fostering an interdisciplinary liaison to achieve the objectives of design - to create environments that complement living activities.

We are dealing here with goals beyond those of a particular professional's charge and knowledge, yet often he becomes morally bound or legally responsible for them - a fate of being a specialist at the end of a delegatory line. I would challenge that where there is a delegation of responsibility (but a fact of our society) a specification should state the design goals in an operational way. In this manner all groups can address the common problem. The rising concern for mandatory environmental impact statements and the precautionary detail in contracts could be taken as a matter of course rather than as an additional burden.

The "performance concept", as presented by the international building research organizations (Atkinson 1971), stresses the physical aspects of design evaluation. Here the measures of a test procedure or analogous structure are compared with values set by performance criteria and appraised accordingly. Design goals apertaining to activities and environmental features are invariably unstated but are assumed to operate through the pre-determined criteria. Those criteria in fact have become sophisticated forms of presently accepted building practice. In consumer language the closest goal statements to be found are related to "user needs" and "user wants". Often these goals are so general and problem embracing that they are not operational because of inherent inconsistencies or contradictions. There are also the situations where the questions are not of "need" or "want" in that the problem may not affect the "user", such as the components of distribution systems (mechanical, power, material). Again, "consumer satisfaction" tends to overlook physiological problems (lead paint poisoning, deafness) where people are unaware of affects by which they might assess their satisfaction. With blase consumer attitudes many problems would not be posed on a satisfaction basis. What is required is a specification that will encourage innovation and alternatives for the promoter and designer - not to tell them what or how to build but rather to consistently suggest ranges of human and environmental criteria to design for.

The convenience of various measures in test procedures may provide control for manufacture and assemblage but in most instances they will not correlate with human responses. Therefore those test measures will be untenable with a design evaluation based on human response criteria, and consequently they may seem unreasonable to designers and irrelevant to the occupants. What we need are stimulus measures (Halldane Oct 1970, Dec 1970) that relate both to human responses and to distribution systems[*1]. For instance measurement parameters (factors) in lighting group into perceptual, stimulus, and distribution categories as follows.

Parameter:			**Units:**
perceptual...	visual magnitude assessment...	luminosity (brightness).	not appl.
stimulus...	luminous planar intensity...	luminance (photometric brightness).	nit
distribution...	luminous power density...	illuminance (illumination).	lux

Illuminance does not correlate with the luminosity because the distribution can involve many changes through variations in surface reflection and transmission. Observe low luminosity in sunlight reflected from dark paper or illuminated windows at night.

[*1] Since this paper presents an interdisciplinary approach some of the terminology will be unfamiliar to the majority of readers. Communication of new concepts and problems beyond those which we have traditionally considered have made this necessary. However, terms used internationally, by professional organizations, and by other disciplines have been adopted. Less definitive synonyms are added in parentheses.

The disciplines that can correlate stimulus and response parameters in perception are distinctly different from those of engineering and physics since the response is a non-physical concept. Psychophysics deals with these problems. A summary of the different parametric categories will be found in the end tabulation but a fuller discussion is left to previous papers (Halldane Oct 1970, Dec 1970, Feb 1971). Differentiation between perceptual and cognitive responses is fuzzy. It is helpful to think of a cognitive selection of perceptual cues and those cues promoting cognitive responses, just as neural responses induce perception and cognition affects overt and physiological responses.

Non-physical parameters of human perception and cognition (covert or "hidden" behavior) can not be measured. Instead we measure either the physical stimulus of the environment, the physiological responses, or the overt behavior (motor activity) of a person that correlate with a specific non-physical parameter. Once a model is established it may be simulated by a measuring instrument. Thus a luminance - luminosity model is simulated by a telephotometer with a lens, filter and sensor which is analogous to the eye system but not to the neural since a photometer does not account for the context and adaptive effects.

2. A specification as a predictive statement for evaluation

Design evaluation is a checking procedure to ascertain whether a design is satisfactory in terms of a particular agreed upon rationale. Design specification is a predictive procedure to anticipate the particular rationale for evaluation. This rationale needs to be timeless and incorporate features that plead for the solution of immediate problems but without being anchored to present day technology. In other words alternative solutions are permitted to stem from the behavioral variations in human goals rather than the reasoning that relates the parameters (synthesis) or that arbitrarily decides their attributes and magnitudes (criteria).

In the development of a specification for design evaluation I believe we can ask four basic categories of questions:

a) What is the design for?	Operational goals.
b) What are the factors to consider in design?	Parameters.
c) How are the factors related?	Synthesis.
d) What attributes and magnitudes are needed for the factors to meet the goals?	Performance criteria.

The tables at the end of the paper illustrate the categories, and the evaluation flow diagram the procedure.

A specification can be used for evaluating design in two independent ways. One way is in a stationary evaluation where the elements of goals, parameters, synthesis and criteria are defined for a specific instance in time over a narrow time domain. Here history is irrelevant. Examples include supervisory tasks, monitoring, periodic reviews, stocktaking, critiques, impulsive purchases, and occupant appraisals. The other way is in a sequential evaluation where the concern is for the evolution in the elements of goals, parameters, synthesis and criteria over time. Illustrations are found in historical reviews, construction programs, inquiry commissions, office schedules, and routine maintenance. A full design specification would permit the sequential evaluation of future events to be more reliable than has been the tradition.

The statement of a design specification requires careful consideration. Present legal systems in this country insist that a written statement takes precedence over other forms. Other legal systems can include the drawings and schedule of quantities. With a concept of performance each parameter of design, both human and environmental, requires qualification. This is achieved through selecting parametric performance criteria to meet the relevant operational design goals. It means that any specification statement should contain all the evaluative elements in any acceptably communicable form such as through a computer program, venn (bubble) diagram, model, analog, microfilm, holograph, graph, table, tape, drawing, written document, code, performance test, or prototype. The extent of a specification depends on the degree of delegation of responsibility from the promoter through designer to contractor, laborer and occupant. A legal framework safeguards the contracting parties in relation to both the delegation of responsibility and the evaluative elements of goals, parameters, synthesis and criteria. Questions of law are customarily based on precedence because of a reliance on inductive reasoning. Now if all the parties agree to a deductive rationale by means of a comprehensive specification it is possible for a legal system to be predictive and anticipatory.

Government management at Federal, State and local levels has a monitoring responsibility to ensure that building is economically dependable, maintainable and capable of supporting the intended human activities. However the goals for this delegation of responsibility are not too clear since government management does not design and construct buildings (except General Services Administration, Army, and Navy). At present it controls physical aspects of design through building codes, requirements for funding, or by reviews of environmental impact statements. With recent legislation concerning desegregation and discrimination cultural and ethnic differences can not be recognized. If government management typifies or generalizes an American culture and extends its building responsibility to include the support of human activities we are likely to find that the heritage of Indian, Chinese, Spanish and Hawaiian expressions will be lost. Instead. where the goals, parameters, synthesis and criteria are clearly specified the cultural differences can augment the alternative design solutions and can show how a proposal fosters desegregation and non-discrimination. As a monitoring organization, government authorities should state the bounds of building in terms of human and environmental factors and allow the inherent differences of people, power and materials to be freely expressed by the promoter, designer and occupant within those accepted bounds. In this way monitoring specifications for the critical parameters will move from distribution systems to those of stimulus systems and human responses.

3. Application of design specifications

The strength of a comprehensive specification as briefly described above is in assisting us to consistently utilize our evolving technology. Where disciplines are clearly defined, both in relation to the correlation of parameters and the flow of evaluative decisions, it is possible to delegate responsibility to the various design personalities. We find that the conceptualization for the specification applies to any form of design whether of buildings, mines, space stations, ships, urban systems, or service programs. In sequential evaluations design can be either predicted or reviewed.

Predictive evaluation is the customary form for the designer. Here the specification illustrates a proposed environment through drawings, schedules and models. A promoter or client is less articulate in extrapolating those statements into his perceptions of the living spaces and relies on the judgement of his agent (architect, planner, engineer) as to whether it will meet his conception. Clearer statements of goals, the use of existing comparative environments, and the experiencing of mockup prototypes would help to alleviate these problems. Where there is a concern for possible adverse environmental situations a monitoring specification must be included. Measurement or test procedures alone are an insufficient specification and goal statements are needed to make the parametric criteria tangible. For instance in developing a lighting standard for coal mines (Halldane Oct 1970) a plausible minimal condition was to set the human goal to avoid scotopic nystagmus, a miner's ocular disease. The problem correlates with a measure of luminance and the parametric criteria become one of a field luminance exceeding 0.05fL to ensure photopic vision. Illuminances on the coal would need to exceed about 5fc since a dark brown coal absorbs considerable light. It is significant that the human response is sufficiently definitive to correlate with a stimulus measure. A further application for a design specification is in structuring a theme for a conference or research program. The value is that each contributant can address specific problems within a conceptual framework and the missing elements can be recognized at an early stage.

Review evaluation is when the formation of an environment is considered at the time of an existing system. Here we can analyse the validity of a specification both in stationary and sequential terms. We can ascertain the degree of anticipated performance at an instance in time, and the changes in the evaluative elements of goals, parameters, synthesis and criteria over time. Consistencies will reflect the appropriateness of the original specification models. For example in the evaluation of mental health facilities it is necessary to review how the various personalities and supporting facilities promote the changes in an affected person's (client, patient) behavior towards his compatibility in the community. Also the promotion, design, construction and occupancy requires a sequential evaluation to see if modifications to the original processes can lead to more effective comprehensive specifications for mental health services and facilities. Controlled experimental studies such as changing the lighting, acoustics or travel paths can augment the value of a review and suggest alternative design possibilities.

4. Conclusion

The performance concept is only viable if the current philosophies are extended to include organismic factors of human, animal and plant life. Further, the success of establishing pertinent performance criteria will rest in deciding appropriate design goals and in defining the parameters consistently. A rational development of environments to support and complement the intended organismic activities is dependent on the accuracy and relevance of the correlation models which relate the parameters.

A rigorous discipline is needed to order the fragmentation of contemporary performance thinking. To this end an interdisciplinary design specification is suggested for evaluating design in terms of operational goals, parameters, synthesis and performance criteria.

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A: OPERATIONAL GOALS OF DESIGN

"What is the design for?"

Operational goals in design are qualifications of a promoter's intentions that are based on the provision for and differentiation between activities.

Qualifying questions for an operational goal:

What?
Where?
When?
How?
Why?

ACTIVITY GOALS:

ENVIRONMENTAL-

ORGANISMIC-

PROVIDING-

Power-

Natural-
Solar
Fossil fuel
Geothermal
Gas

Derived-
Electrical
Nuclear
Mechanical
Structural
Light
Sound
Thermal

Material-

Organic
Geologic
Topographic
Oceanographic
Atmospheric

Plastic
Metallic
Wood
Cement
Glass

Physiological-

Metabolic
Muscular
Respiratory
Transpiratory
Endocrinic

Behavioral-

Feeding
Procreative
Excremental
Migrative
Egress
Sleeping
Leisure
Productive
Communicative

DIFFERENTIAL-

Physical-

Structural
Quantal
Periodic
Dynamic
Kinematic

Genotypic-

Individual
Group
Community
Sex
Age
Deviant
Periodic
Cultural

Taxonomic-

Human
Domestic animal
Horticultural
Animal
Plant

B: PARAMETERS OF DESIGN

"What are the factors to consider in design?"

DESIGN ACTIVITY PARAMETER:

<table>
<tr><td colspan="2">ORGANISMIC RESPONSE</td></tr>
<tr><td>STIMULUS</td><td rowspan="2">ENVIRONMENTAL SYSTEM</td></tr>
<tr><td>DISTRIBUTION</td></tr>
</table>

ORGANISMIC RESPONSE-

PHYSIOLOGICAL-

BEHAVIORAL-

OVERT-

COVERT- [NON-PHYSICAL]

INDIVIDUAL-

PHYSIOLOGICAL

Characteristic-
- Metabolic
- Muscular
- Neural
- Respiratory
- Transpiratory
- Circulatory
- Homeostasic
- Endocrinic

Measurement-
- Temperature [rectal, mouth]
- Blood [type, count, pathogens]
- EEG
- ECG
- EMG
- Pathogen count
- Pressure [blood]

OVERT

Characteristic-
- Walking
- Talking
- Orienting
- Sitting
- Standing
- Eating
- Producing
- Training

Measurement-
- Movement [direction, displacement, velocity, acceleration]
- Fixation
- Productivity [operations/time]
- Consistency [deviation from individual mean]
- EOG
- Pulse rate

COVERT

Characteristic- Assessment-

PERCEPTUAL-

Characteristic-	Assessment-
Visual	Luminosity
Auditory	Hue
Skin	Saturation
Proprioceptive	Contour clarity, separation
Olfactory	Flicker
Gustatory	Depth
Organic	Motion
	Form
	Loudness
	Pitch
	Warmness
	Coolness
	Roughness

COGNITIVE-

Characteristic-	Assessment-
Resolvent	Descriptive
Impressional	Acceptability
Associative	Likeness
Phobic	Need
Learning	Empathic
	Evaluative

SOCIAL-

PHYSIOLOGICAL

Characteristic-
- Couple
- Family
- Group
- Community [public health]
- Regional
- Racial

Measurement-
- Probability
- Disease incidence
- Treatment incidence
- Birth rate
- Death rate

OVERT

Characteristic-
- Couple
- Family
- Group
- Urban block
- Community [public education, welfare]
- Regional
- Cultural

Measurement-
- Probability
- Population
- Population density [organisms/area]
- Communication frequency
- Movement pattern
- Participation frequency

Parameters continued....

B: Parameters continued....

ORGANISMIC RESPONSE	
STIMULUS	ENVIRONMENTAL SYSTEM
DISTRIBUTION	

DESIGN ACTIVITY PARAMETER:

ENVIRONMENTAL SYSTEM-

STIMULUS-

RESPONDABLE-

Characteristic-	Measurement-
POWER-	
Light	Luminous planar intensity [luminance] Chromatic planar intensity [tristimulus flux]
Sound	Auditory power density and sound pressure density [weighted sound pressure level, effective perceived noise level] Frequency
Thermal	Thermal power [energy/time] Thermal power density Temperature
Erythermal	Erythermal energy density [energy/area]
Ionizing	Ionizing energy capacity [ions/mass, radiation dose]
Movement	Proprioceptive power and energy
Holding	Holding power and energy
Skin movement	Static and sliding frictional power and energy
MATERIAL-	
Surface	Curvature Displacement
Air	Dry and wet bulb temperature
Vapor	Vapor pressure
Solute	Material concentration
Water	[mass portion/volume]
Sweat	Material volume
Food	[volume portion/volume]
Aerosol	Material capacity
	[mass portion/mass]
	Material flow rate
	[mass/time]
	Stereochemical

FIELD-

Characteristic-	Measurement-
PATTERN-	
Co-ordinate	Polar [$\theta, \emptyset$]
Contour contrast	Contour contrast gradient Contour spacing
Areal, planar	Luminous area Luminous density [area/area]
Spectral	Chromatic power Instantaneous sound power spectrum [real time analysis]
SEQUENTIAL-	
Pulse	Stimulus power and energy per perceptual sampling period
Intermittent	Stimulus energy modulation
Progressive	Stimulus time modulation ratio
Relative movement [ocular, head, behavioral]	Sound power progression
ORIENTING-	
Co-ordinate	Spatial polar [$\theta, \emptyset\ \theta', \emptyset'$ ...]
Phototropic	Phototropic directive
Audiotropic	Audiotropic directive
Thermotropic	Thermotropic directive
Air movement	Directive [asymmetrical field function]
SPATIAL-	
Distal shape	Gradient
Sound decay	Interposition
Air movement	Relative movement
	Relative size
	Reverberation time

Parameters continued....

B: Parameters continued....

ORGANISMIC RESPONSE	
STIMULUS	ENVIRONMENTAL SYSTEM
DISTRIBUTION	

DESIGN ACTIVITY PARAMETER:

ENVIRONMENTAL SYSTEM-

DISTRIBUTION CO-ORDINATING-

CONVERTING-		TRANSFERRING-	
Boundary characteristic-	Boundary measurement-	Boundary characteristic-	Boundary measurement-
POWER-			
Surface-	Cartesian co-ordinate [X,Y,Z].	Surface-	Cartesian co-ordinate [X,Y,Z]
Emitting	Power converting efficiency	Reflecting	Power transferring efficiency
Absorbing	[power converted/original power]	Diffusing	[power transferred/incident power]
	Power	Diffracting	Power
Laminar-	Energy	Conducting	Energy
Absorbing	Power and energy density	Laminar-	Power and energy density
	Power and energy intensity	Transmitting	Power and energy intensity
Spatial-	Power and energy planar intensity	Conducting	Power and energy planar intensity
Ionizing	Potential [temperature,voltage,	Refracting	Potential difference [difference
	position]	Polarizing	in temperature, voltage, charge,
Formal-	Flow rate [current, thermal]	Diffusing	position]
Power plant	Force	Viscous	Flow rate [current, thermal]
Generator	Pressure and stress [force/area]	Spatial-	Force
Converter	Cost	Diffusing	Moment [force.length]
Lamp	Unit cost [cost/measurement unit]	Formal-	Pressure and stress [force/area]
		Heater,cooler	Cost
		Structural	Unit cost [cost/measurement unit]
		Floor, wall,	
		ceiling,roof	
+power stimuli	+power stimulus measures	+power stimuli	+power stimulus measures
MATERIAL-			
Surface-	Dimension [X,Y,Z]	Surface-	Dimension [X,Y,Z]
Corrosive	Material converting coefficient	Capillary	Material transferring coefficient
Combustive	[mass converted/original mass]	Adhering	[mass transferred/incident mass]
Condensing	Velocity	Laminar-	Velocity
Laminar-	Humidity ratio	Porous	Density [mass/volume]
Cement setting	[mass water/mass dry air]	Penetrating	Strain [length change/length]
Photochromic	Mass	Adsorbing	Mass
Spatial-	Volume	Spatial-	Flow rate [mass/time]
Combustive	Cost volume [cost/volume]	Ventilating	Volume
Fogging	Cost capacity [cost/mass]	Convecting	Cost
Formal-	Cost density [cost/area]	Diffusing	Relative cost
Fire	Cost rate [cost/time]	Formal-	[unit cost/total cost]
Waste		Vehicular	Cost distance [cost/distance]
conversion		Construction,	
		maintenance,	
		demolition	
+mat. stimuli	+material stimulus measures	+mat. stimuli	+material stimulus measures

C: SYNTHESIS OF DESIGN PARAMETERS

"How are the factors related?"

Synthesis is an inductive or deductive method of reflective reasoning. The concern is to establish a correlation between the parameters which in turn consolidates a corresponding discipline. Validation of the correlation model in design is dependent on an application to relevant operational activity goals.

PARAMETRIC CORRELATION METHOD:

INDUCTIVE-

PRECEDENT ARGUMENT-

Advisory
Apparent reasonableness
Replicative

ANALOGOUS ARGUMENT-

Duplicative
Simulative

AUTHORATIVE ARGUMENT-

Mandatory code or standard
Managerial decision
Renowned personality
Adversarial process

DEDUCTIVE-

PHYSICAL-

Disciplines:

Physical parameter - Physical parameter

envirophysics,
physiophysics, envirophysiology,
behaviophysics, envirobehavior,

DIRECT-

Measurement-
Power converting and transferring efficiency
Material converting and transferring coefficient
Mass, length, time ratio

COMPARATIVE-

Reference measurement-
Relative power converting and transferring efficiency
Relative material converting and transferring coefficient

Graphical model-
Rectangular X,Y,Z
Polar $\theta,\emptyset$
Diagramatic
[venn, power, material, force, moment, psychrometric, distribution]
Nomographic

Simulative model-
Scaled [distribution of light, sound, people, building elements]
Analog [physical, digital]
Mathematical [statistical, tensor, functional transform]
Material [molecular, ionic]
Testing [material, system]

PSYCHOPHYSICAL-

Disciplines:

Stimulus physical parameter - Response assessment parameter

psychophysics, enviropsychology

Communication-
Identifying
Ordering
Pairing
Equating
Scaling
Appraising

Reference stimulus-
Comparing
Adjusting
Limiting

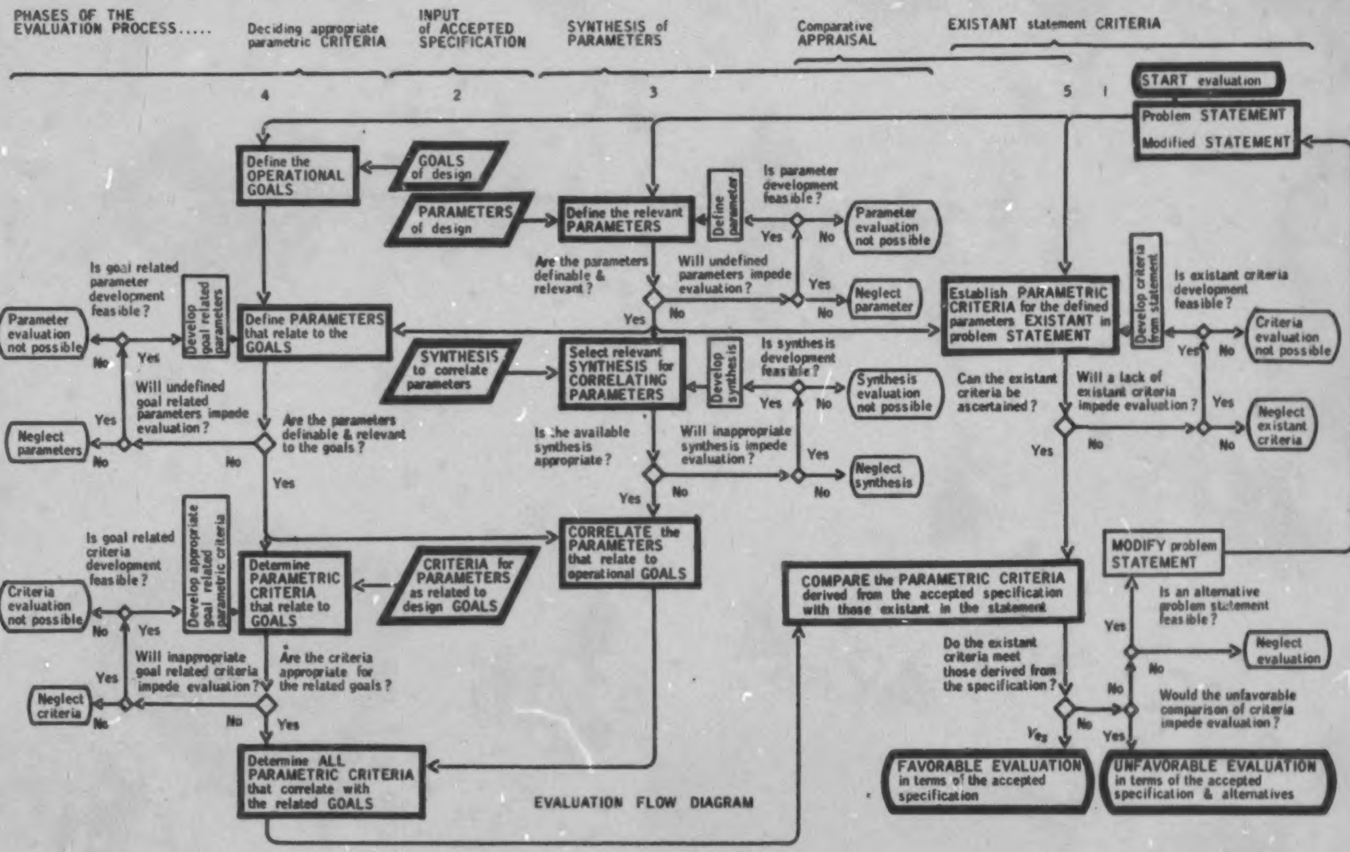
Simulative model-
Psychophysical
Psychoneural
Analog [photopic telephotometer, weighted sound pressure meter]

D: PARAMETRIC CRITERIA FOR DESIGN EVALUATION

"What attributes and magnitudes are needed for the factors to meet the operational design goal?"

PARAMETRIC PERFORMANCE CRITERION:

PHYSICAL-		NON-PHYSICAL-	
Attribute-	**Magnitude-**	**Attribute-**	**Magnitude-**
PROVIDING-			
Activity event [selected goal-oriented event] Binary event [yes-no, go - no go]	Zero Minimum Operational Transitional Optimum Maximum	Unnoticeable [adapted] Order Assessed Contextural	Threshold Minimum Assessed Transitional Acceptability Maximum Intolerable
COMPARATIVE-			
Identical Co-ordinating Functional [safety, user] Simulating Replicating	Identical Proportional Probability	Identical Intermodal Dominant mode Political Ethical Stylate	Identical Relative Majority vote
SEQUENTIAL-			
Forming Maintaining Changing [flexible, ecological] Demolishing	Growth Obsolescence Decay	Learning Recalling Comprehending	Adaptive


PHASES OF THE EVALUATION PROCESS.....
Deciding appropriate parametric CRITERIA
INPUT of ACCEPTED SPECIFICATION
SYNTHESIS of PARAMETERS
Comparative APPRAISAL
EXISTANT statement CRITERIA
4
2
3
5
1
START evaluation
Problem STATEMENT
Modified STATEMENT
Define the OPERATIONAL GOALS
GOALS of design
PARAMETERS of design
Define the relevant PARAMETERS
Define parameter
Is parameter development feasible?
Yes
No
Parameter evaluation not possible
Are the parameters definable & relevant?
Will undefined parameters impede evaluation?
Yes
No
Neglect parameter
Yes
No
Establish PARAMETRIC CRITERIA for the defined parameters EXISTANT in problem STATEMENT
Develop criteria from statement
Is existant criteria development feasible?
Yes
No
Criteria evaluation not possible
Is goal related parameter development feasible?
Develop goal related parameters
Parameter evaluation not possible
No
Yes
Define PARAMETERS that relate to the GOALS
SYNTHESIS to correlate parameters
Select relevant SYNTHESIS for CORRELATING PARAMETERS
Develop synthesis
Is synthesis development feasible?
Yes
No
Synthesis evaluation not possible
Can the existant criteria be ascertained?
Will a lack of existant criteria impede evaluation?
Yes
No
Neglect existant criteria
Yes
No
Will undefined goal related parameters impede evaluation?
Yes
No
Neglect parameters
Are the parameters definable & relevant to the goals?
No
Yes
Is the available synthesis appropriate?
Will inappropriate synthesis impede evaluation?
Yes
No
Neglect synthesis
Yes
No
Is goal related criteria development feasible?
Develop appropriate goal related parametric criteria
Criteria evaluation not possible
No
Yes
Determine PARAMETRIC CRITERIA that relate to GOALS
CRITERIA for PARAMETERS as related to design GOALS
CORRELATE the PARAMETERS that relate to operational GOALS
MODIFY problem STATEMENT
COMPARE the PARAMETRIC CRITERIA derived from the accepted specification with those existant in the statement
Is an alternative problem statement feasible?
Yes
No
Neglect evaluation
Will inappropriate goal related criteria impede evaluation?
Yes
No
Neglect criteria
Are the criteria appropriate for the related goals?
No
Yes
Do the existant criteria meet those derived from the specification?
Would the unfavorable comparison of criteria impede evaluation?
Yes
No
No
Yes
Determine ALL PARAMETRIC CRITERIA that correlate with the related GOALS
FAVORABLE EVALUATION in terms of the accepted specification
UNFAVORABLE EVALUATION in terms of the accepted specification & alternatives

EVALUATION FLOW DIAGRAM

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

Human Requirements for Buildings

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We build in order to establish certain required environmental conditions.

This set of conditions should be according to the users' requirements. This paper will discuss the users' activities and the users' characteristics as a basis for defining the users' requirements. Further we discuss a possible procedure for identifying the requirements and indicate the use through examples. The paper holds that it is necessary to take the variations in user's characteristics into consideration when defining the requirements. Further the paper tries to expand the use of users' activities to include all kinds of activities that may have consequences for the physical solution. The intentions of what is put forward here is to initiate a further discussion of the continuation of this kind of work. It is not meant to give a solution to these problems.

Nous bâtissons pour établir certaines conditions requises d'environnement.

Cette série de conditions devrait être en accord avec les exigences des usagers. Pour définir les exigences des usagers, cette communication prend comme base les activités et les caractéristiques des usagers. En outre, nous soumettons une méthode possible d'identification des exigences et nous expliquons son emploi par des exemples. La communication affirme qu'il est nécessaire de considérer les variations des caractéristiques des usagers pour définir des exigences. En outre elle essaie d'étendre la prise en compte des activités des usagers, de façon à y inclure toutes sortes d'activités susceptibles d'influencer la solution physique. L'intention des auteurs est de provoquer une discussion quant à la poursuite de ce type de recherches. Il n'est pas question de livrer une solution à ces problèmes.

Key words: Human activities; performance criteria; physical environment; planning and design basis; user characteristics.

1. Introduction

We build in order to establish certain required environmental conditions.

This set of conditions should be according to the users' requirements. In this paper we will concentrate on the humans as users, though the principles will be the same for other "users", - things, machines, animals etc.
There are principally two different approaches to the problem of defining the users' requirements.

One is to start with the activities, and users' characteristics, trying not to be limited by traditional concepts of buildings.

The other approach is to derive the functional requirements from existing buildings.

The first approach seems to be the most difficult, but is considered as giving more room for innovation. The question is whether we can make it operative with the present level of knowledge on human requirements. Derivations from existing solutions are considered to leave less room for innovation, but are likely to be a more operative method today.

The choice of approach should be made in relation to the problem to be solved. When wanting to develop entirely new products, one should start with the human requirements. To improve known products the second approach may be the most convenient. The purpose of this paper is to contribute to the discussion of the first approach, starting with the users' activities and the users' characteristics.

The following is based on a simple model Figure 1, showing the relations between the most important concepts we use in this paper and their relations to the analysis of the requirements in building.

This paper will discuss:

- users' activities
- users' characteristics
- procedures for identifying requirements
- examples to indicate the use
- continued work

The intention of what is put forward here is to initiate a further discussion on the continuation of this kind of work. It is not meant to give a solution to these problems.

2. Users' Activities

2.1 Identifying Users' Activities

Identifying users' requirements for buildings means to investigate the functional relationship between the users and the buildings. We have chosen the users' activities as the starting point for this, for the following reasons:

- users' activities may express the function of a building
  we build to make certain activities possible.

- users' activities express the users' reaction/adaptation to the building.

Activities have functional consequences both for the users and the buildings and therefore may form a link between the two in a functional analysis.

The activity concept has in different contexts been given varied definitions.

Some definitions emphasize the purpose of the activity, some the performer of the activity, some the activity as a process.

For the purpose of this discussion the definition given in Webster's new collegiate dictionary is sufficient; activity: "State of action or quality of being active".

One cannot study all possible activities, one must concentrate on activities

- important to the user
- affected by the design of the building
- which affect the design of the building

We may think of the following ways to guide the choice of relevant activities:

a) Choice in cooperation with the actual user groups. This would be a democratic approach, but the result may only be relevant for the buildings experienced by the users. Through cooperation one might be able to cut through these limitations to some extent.

b) Choice based on theoretical studies (for instance through physiology, psychology, sociology).
This means that knowledge from different disciplines has to be coordinated, which is often a problem. Data in the field of human sciences are very often limited to an experimental context which makes generalization difficult.
However, it is here the possibilities of including "neglected" or "forgotten" activities and to "discover" new activities are.

c) Choice guided by results of surveys, enquiries etc. from other user groups.
Results from these are often limited to special conditions and by users' experience. It demands great insight into the users' situation from the interpreter of the results.

d) Choice based on directly observed behaviour.
This is in addition limited to activities directly available through observation.

e) Choice guided by the analysis of existing buildings.

The three last types of data are of most use for this purpose when gathered for identifying existing problems. By surveying these, one's ability to choose relevant activities will increase.

There is a tendency to choose activities available for observation with a clearly defined purpose. This leads to marginal improvement for performing these activities, while requirements based on other activities are not considered at all.
A description of for whom and under which conditions the activity may be observable, is of interest from the methodological point of view, to stimulate the studies of the more difficult observable activities.

To improve the basis for an activity analysis and to reduce a biased selection of activities one has to combine these different approaches, as the value of activity studies for the quality of design will greatly depend on the choice of activities.

The problem of to what extent one should go into detailed activity studies is closely connected to the problem of choosing the activities.

The study has to be detailed enough for identifying the requirements and still be generally relevant.

One should consider the danger of getting biased results when studying some activities in more detail than others.

We do not think it possible to develop a rigid system for detailing all types of activities. The degree of detailing must be considered in relation to the design problem.

Activities with a clearly defined purpose are usually more available for observation than for example the process related activities.

2.2 Analyzing the Activities

In the following we will discuss some aspects by which the activities may be analyzed.

a) By whom is the activity performed?
To define the users' requirements on the basis of an analysis of the users' activities, we have to identify the person(s) performing the activities. The users' characteristics, the number of users and their relations have to be included in the activities analyzed.
This type of study has been carried out for certain activities and certain categories of users. It has been used for describing household activities, and also in studying the fitness of a building for disabled people.

But most activity studies operate with a generic user concept which is of limited value.

b) What is needed to perform the activity?
What is the sensory stimulation needed?
(e.g. temperature, humidity, air movement,light, sound, smell, taste)
What is the consumable supply needed? (e.g. air, water, energy, goods).

c) What are the by-products of the activity?
Usually an activity results not only in fulfilling the expressed purpose, but it also has by-product effects both for the performer and the environment. It is necessary to study the total result of the activities. What are the satisfactions, dissatisfactions, by-products produced by the activity?

d) Where is the activity performed?
What space, spatial relations and spatial boundaries are required to perform the activity?
This is the most common starting point for an analysis of activities related to design of buildings.

e) What is the purpose of the activity?
All activities have a purpose, even process related activities like breathing, thinking, seeing, hearing etc..
The purpose may be clearly defined as an expected result, but it may also be obscure and unconscious. For some activities the purpose is easy to describe (ex. to eat, sleep etc.), for others it is difficult (ex. to dominate, to protect, to love).
Some activities start with a decision by the user, others are processes we go through without controlling the beginning and end.
The purpose of a particular activity may be different depending on by whom, when and where the activity is performed.
This is important to describe as the only way to measure the efficiency of an activity in relation to the purpose.

f) Activities and time aspect.
Activities may be described according to time spent, when it is performed and how often it occurs.
Also the sequence and interdependence of different activities in time is relevant.
Time spent and how often the activity occurs may indicate the importance of the activity both for the user, and so for the design of buildings.
The sequences and the interdependence of activities may be of great importance when defining the functional relations between different parts of buildings, activity aids and the surroundings.

g) Movements required to perform the activity.
The pattern of movements is relevant for giving dimensions to space and equipment and for their inter-relations.
The movements required for a certain activity will vary, depending on users' characteristics.
The movements for a particular activity for disabled persons, aged, children and adults will be different.

3. Users' Characteristics

To identify users' requirements a thorough knowledge of users' characteristics is necessary, involving many different disciplines, each with different terminologies and approaches. This information no doubt is available to a large extent, but very little has been done so far in structuring, coordinating and surveying information from the different theoretical starting points to form a basis for design. This is an important task in future work. This is only a starting attempt to outline the information necessary to identify the requirements posed by different user groups. We will only be interested in characteristics which influence the relationship between user/building.
The users' characteristics are traditionally divided into physiological, psychological and sociological categories. If we go into greater detail, we find that it is very difficult to draw sharp lines between the three. The characteristics must not be treated statically, one must emphasize the changes through life span and consider individual variations.

3.1 Physiological Characteristics

a) - Neural development.
The nervous system is the coordinator of our responses. It provides extensive connections with all parts of the body to integrate various stimulations and responses. Information about the nervous system is helpful to understand the development of psychological processes as learning, memory, intelligence and emotions.

b) - Glandular development.
The system of glands maintains and regulates the chemical balance of the organism. Like the nervous system it is of great importance to behaviour. Some knowledge of this is necessary to understand such processes as skeletal, muscular and emotional development.

c) - Physical development.
Physical changes occur continuously throughout life. The changes in size and proportions, in the skeleton, muscles, or internal organs occur in certain sequences that are of importance in design. The structural changes influence the intellectual, emotional and personality characteristics of the individual.

d) - Motor development.
Motor development, especially locomotion skills and manipulatory abilities, are important for one's scope of environment.

e) - Sensory development.
The environment influences man through his senses: hearing, vision, taste, smell and cutaneous sensitivity.

3.2 Psychological Characteristics

a) - Learning and maturation.
Maturation refers to the development of behaviour due to inherited factors. Learning is dependent on experience. Learning and maturation are both of great importance to man's relation to environment.

b) - Intellectual development.
Intelligence has been defined as "the capacity for flexible adjustment", (Munn 1938) or "the degree of availability of one's experiences for the solution of problems", (Goddard 1948). These definitions indicate that intellectual development refers to man's ability to adjust to environment. Under this heading one could treat: remembering, imagining, thinking and reasoning, and concept formulation.

c) - Emotional development.
Emotional development is influenced by environment, both the physical and the mental, and is a determinant to social adjustment.

3.3 Social Characteristics

From infancy to old age man goes through a process of social development. He learns how to act and think in relation to others. He develops his personality and interests in relation to others. He learns how to function as part of his society. This is for most people a difficult and some times painful process. The social situation of a person or a group will strongly influence the requirements and the environment is one of the determinants of the social development.
One therefore has to know the main traits in the process of social development and the main characteristics of the social situation of a person or a group to identify the requirements.

3.4 Age Categories

The users' characteristics are a question of development through life-span. It is, therefore, necessary to use age categories as guidance for the description of the users' characteristics.
An operative division into age categories has to correspond to the major changes of the different aspects of developmant of users' characteristics.
We have so far found it convenient to use the following age categories:

I	Pre-school-age		0- 6 years
	subdivision:	0-1	
		1-3	
		3-6	
II	Middle childhood		7-12 years
III	Adolescence		13-20 years
	subdivision:	13-15	
		16-20	
IV	Adulthood		21-25 years
			26-64 "
V	Old age		65- ......

4. An Outline of a Procedure for Identifying Users' Requirements

4.1 Choosing Activities Relevant to the Function of the Building

(Outlined in chapter 2). We are not able to present a ready made activity list for all kinds of buildings. Different types of lists will be needed depending on:

a) what is the intended use of the building
b) by whom the building will be used

4.2 Defining the User(s) and their Relevant Characteristics

(Outlined in chapter 3). As for activities we are not able to present an overall list of relevant user characteristics. Different types of lists will be needed depending on:

a) which activities will be considered
b) which age categories will be considered

4.3 Identifying User's Requirements

On the basis of the information from points 4.1 and 4.2 as they have been discussed in parts two and three we may identify and survey what is required of the building for the different user(s) to carry out the necessary and desired activities, for which the building is to provide a framework. As the detailed requirements will be dependent on the choice of relevant activities and user characteristics we shall only consider the problems of stating and structuring the requirements in an operative way and under chapter 5 give some examples on how to combine the information of 4.1 and 4.2.

Stating and structuring the requirements:

These requirements should be stated:
- in terms recognizable and relevant to the user
- independent of the given conditions
- as qualitative and/or quantitative information depending on information available.

After studying different ways of structuring requirements for the building (as level), we have used the following headings for grouping the requirements:

a) Requirements of accessibility/usability refer to the easy and comfortable access to the attribute and its qualities necessary or desirable for the use of the building or its parts when performing the activity.

b) Requirements of safety/protection refer to the qualities of the attributes concerning the personal safety with regard to injury and other risk factors for the health and well-being of the occupants as well as the protection of his property.

c) Requirements of perception/comfort according to the user's reaction(both psychological and physiological) on the built environment, his structuring of the information in it, and the ability to orient and identify himself.

d) Requirements of social adjustability according to social changes of the occupant(s), for instance in need for contact or privacy when the different activities are taking place.

Durability or the possibilities of controlling or regulating the qualities of the attributes as a function of time are not taken up as a separate aspect to the requirements, but should be implicitly stated in each requirement (especially accessibility/usability).

4.4 Required Performance of Building Hardware

The users' requirements must be related to given conditions in order to find out what performance is required of the building hardware. The performance requirements have to be structured in a way operative to design. This will be discussed in another paper.

5. Examples Indicating Relations between Activities/Users' Characteristics and Requirements

Activities like

to breathe
to eat
to drink
to sleep
to rest
to sweat
to urinate
....
....
....
....

considered in relation to user's physiological characteristics will be relevant for the requirements of accessibility/usability (access to air, food etc.).

Activities like

to hear
to see
to smell
to taste
to feel

considered in relation to user's physiological sensory development will be relevant for the requirements of perception/comfort (reaction to appearance, touch, information in the built environment, etc.).

Activities like

to walk
to run
to jump
to sit down
to stand up
to drive
to ride
to swim
to slide

considered in relation to the user's physiological/motor development will be relevant to the requirements of accessibility/usability (access and use of space, stability of structure etc.).

Activities like

to hold
to lift
to carry
to open
to close
to turn
to push
to pull
....
....

Especially relevant to the age groups in which increase or decline in manipulatory abilities occur. Relevant to requirements of accessibility and usability (opening windows, using equipment etc.).

Activities like

to fall
to get burned
to get squeezed
to slip
to drop something
to spill
to collide
....
....

Relevant to safety requirements (safe circulation in a building, danger when using equipment etc.).

Activities like

to protest
to reject
to contact
to isolate
to join
to dominate
to submit oneself
....
....

Especially relevant to the adolescence groups characterized by strong changes in social development.

Activities like

to recognize
to understand
to remember
to orient oneself
to identify
....
....

Considered in relation to users' sensory/intellectual development will be relevant to requirement of perception/comfort and also to the requirement of social adjustability.

Activities like

to give birth
to grow up
to marry
to grow old
....
....

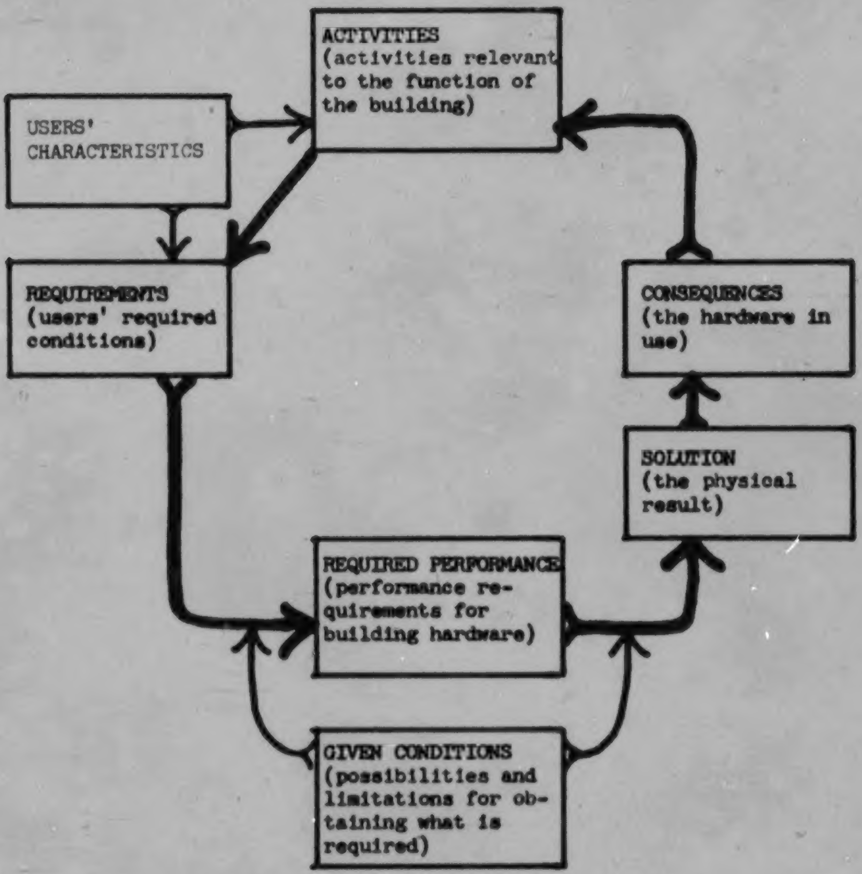
will be relevant to the requirements of usability and social adjustability of the built environment; provision for changes in activity over the functional life of a building.

6. Consequences on the Continued Work

Development of the basic information on the users' characteristics must be carried on, both as theoretical studies and in relation to solving special problems. In connection with this information activity lists must be worked out as a basis for choosing relevant activities.

Different ways of identifying, analysing and structuring the users' requirements should be tried out, revised and adapted to particular needs in design to ease the communication with the users, and between different fields of research.

Fig. 1 Conceptual framework


ACTIVITIES (activities relevant to the function of the building)
USERS' CHARACTERISTICS
REQUIREMENTS (users' required conditions)
CONSEQUENCES (the hardware in use)
SOLUTION (the physical result)
REQUIRED PERFORMANCE (performance requirements for building hardware)
GIVEN CONDITIONS (possibilities and limitations for obtaining what is required)

Comments

Identifying human requirements involves two different types of information that both have to be available and structured in an operative way to guide the design of buildings:
- information on the users' characteristics combined with
- information on the users' activities

On this basis, the users' requirements may be identified.
The users' requirements combined with information about the given conditions will form the basis for stating the performance required. The given conditions will also decide what performance actually will be obtained, through balancing the performance required and the resources available in a cost/benefit analysis. The obtained performance, the solution, will have consequences on the activities actually possible, and thus form the information for the feed-back of the system. (Based on a similar model developed by Tarja Cronberg).

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On Structuring Performance Requirements for Buildings

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This paper treats the problem of transforming users' requirements into relevant properties of a physical solution. From users characteristics and activities we arrive at the required environmental conditions. Together with the data from the given conditions, this forms the basis for the performance requirements. These (data) must be structured in a way making it operative for design. By classifying the requirements according to their basic functions we are able to get, from this point to a set of properties relevant for a chosen type of physical system.

Cette communication traite le problème de la transformation des exigences de l'usager en propriétés pertinentes d'une solution physique. Partant des caractéristiques et activités des usagers, nous arrivons aux conditions d'environnement requises. Avec les informations sur les conditions données, ceci forme la base des exigences de performance. Ces informations doivent être codifiées de façon à les rendre opérationnelles dans le projet. En classant les exigences selon leurs fonctions fondamentales, nous pouvons accéder, à partir de là, à une série de propriétés pertinentes pour un type choisi de système physique.

Key words: Organization of performance factors; performance requirements; required conditions; users' activities; users' characteristics.

Introduction

We build in order to establish certain required environmental conditions.

This set of conditions should be according to the users' requirements. In this paper we will concentrate on the Human as user, though the principles will be the same for other "users", - things, machines, animals, etc.
There are principally two different approaches to the problem of defining the functional requirements.

One is to start with process of use, activities, and user characteristics, trying not to be limited by traditional concepts of building.

The other approach is to derive the functional requirements from existing solutions.

This paper, like the paper entitled "Human Requirements on Building" deals with the first approach. We conclude there with an outline of a procedure for identifying the users' requirements, and of relating these to properties of the building hardware, in the following steps:

A. Choosing activities relevant to the function of the building (ex. dwelling, education, production etc.).

B. Defining the user/user groups and their relevant characteristics.

C. Relating information on users' characteristics to the activities relevant to function of the building. On this basis one may identify and survey what are the required conditions for different user/user groups for carrying out the activities. The required conditions have to be structured in a way operative for communication with users.

D. The users' requirements must be compared with the given conditions in order to find out what performance is required of the building hardware. These performance requirements have to be structured in a way operative to design.

We know that humans will perform according to their characteristics and choice of activities, provided they have acceptable conditions. Our problem is transferring the users' requirements into performance requirements on the building hardware. Further, we try to relate the physical properties of the building hardware to the function of the building. In order to do this, we must analyze the functional relations between the use, and the building, as well as the given conditions.

The information items about the given conditions are structured in accordance with the required conditions, - they are not treated separately in this paper.

This paper treats the analysis on one level, - that of the building/shelter.

The paper "Human Requirements on Buildings" discusses the procedure previously given in points A, B, C. In this paper we will discuss the points C and D.

Man's activities may be regarded as the process of adapting to stimuli from the environment.

In order to perform man will need some input, this can be divided into sensory and consumative. He will need a frame[1] for his performance, and when performing he will produce. The environment will have to cater to his input, provide a framework, and take care of that which he produces.

The existing environment will (more than) often not be according to the conditions man requires for his activities. Therefore it will be necessary to create those required conditions.

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[1] This does not refer to a physical framework, but is an abstract concept for enclosing space and climate.

If we have one environment (i.e. the given), and want to create another, we will need to introduce some hardware. This may then both act as a source for required stimuli, as well as take care of the differences between the required conditions and the given conditions.

This building hardware must therefore have a "function" to take care of these differences. It should provide the required frame, climate and space. Further we must have channels for supply and waste to handle the required services. See Figure 1.

The building, as part of the environment, may then be regarded as having the following basic requirements in relation to man's activities:

- As a source for man's stimuli
  (e.g. the appearance of a building)
- As a frame for man's activities
  (e.g. space and climate)
- As a filter of stimuli from outside
  (e.g. keeping traffic noise out)
- As a filter of stimuli from inside
  (e.g. provision of privacy)
- As having a set of in/out channels
  (e.g. electricity, telephone/garbage, sewer etc.)

This is brief outline of the concept our analysis is based on. See Figure 2.

Our framework has been established in order to structure the physical properties of building hardware, according to the basic functions of the building. This is necessary to form the link between functions and physical properties. It will provide the opportunity to define the properties precisely, according to the required conditions.

Structuring the Performance Requirements

We will now deal with the analysis in more detail.

1.a) In order to perform certain activities man will need a certain "input", sensory and consumable. The sensory input may be related to:

Temperature
Humidity
Air/gas
Radiation
Light
Sound
Odours
Flavor
Shape/form
Surface characteristics

b) This will be provided by the source functions. The consumable input will relate to the supply in channels:

Air
Water
Nourishment
Energy
Aids

2. When performing activities man will produce:

Air/gas
Heat
Humidity
Fecal/urine
Sound
Odours
Forces
Garbage/water

This will have to be taken care of by the filtering(out) functions or the out channels.

3. The building hardware will form a frame for his performance. This frame is divided into space and climate. The space will be characterised by:

Spatial identities
Spatial relations
Spatial boundaries

This will be taken care of by the enclosure. Climate will be characterised by:

Air/hygro/thermal
Movements
Radiation
Light
Sound
Odours

The building hardware will have to have a filtering function to take care of the differences between the given conditions and the required conditions (built environment).

4. The basic functions necessary will relate to the following:

Temperature
Humidity
Water
Air Movement
Air/gas
Radiation
Electric current
Magnetic forces
Light
Sound
Smell/taste
Fire

Conclusion:
The performance requirements on the building hardware may therefore be listed under the following basic headings according to functions:

Source
Enclosure
Filter in
Filter out
Channels in
Channels out

This is an operative way of structuring the performance requirements, as it enables us to handle the requirements independent of the means to be used to solve the problems.

For design purpose it is now necessary to list the relevant physical properties in accordance with these basic functions.

Listing of physical properties, on the building level, relevant for the means to meet the functional requirements, and to withstand the effects of these.

1. Source:

HEAT
Heat capacity
Radiation of heat
Heat conductivity
Warmth to touch
Effects of heat

HUMIDITY/WATER
Emission
Effects of humidity/water

LIGHT
Transmission
Absorption
Refraction
Reflection
Emission of Light
Effects of Light

SOUND
Generation
Reflections
Absorptions
Emission
Effects of Sound

ODOURS
Emission

FLAVOR
Emission of Flavor

SURFACE
Evenness
Flatness
Friction
Effects of Touch

2. Enclosure/space:

DIMENSIONS
m
m^2
m^3

SHAPE
Proportions
Angles

RELATIONS
Function Distance
Connectedness

3. Filter in/out.

FORCE (loads)(e.g. loads caused by wind, snow, activities, intruders, etc.)

Mechanical/structural
Strength

Vertical
Lateral
Racking
Abrasive

Deformations

Compression
Elongation
Deflection
Twisting
Warping

Vibrations

Amplitude
Frequency
Dampening

THERMAL
Heat Transfer

Conduction
Convection
Diffusion
Radiation

HUMIDITY/WATER
Water Permeability
Water Tightness
Vapour Permeability
Effects of Humidity/water

AIR/GAS
Permeability
Leakage
Effects of air/gas

RADIATION
Permeability
Effects of Radiation

ELECTRIC FORCES
Conductivity

MAGNETIC FORCES
Effects of Electricity
Effects of Magnetic Forces

LIGHT
Transmission
Absorption
Refraction
Reflection
Effects of Light

SOUND
Transmission
Absorption
Reflection
Effects of Sound

FIRE
Generation
Combustion
Resistance
Effects of Fire

4. Channels in/out, each involving Content, Capacity, Connections, and Control.

Air Gas
Water/Liquid
Energy

Electronics
Goods
People

Light
Sound

The physical properties are now structured according to the basic functional systems of a building. By having our basis information structured in such a way, we will be able to use it independent of choice of physical systems.

A choice of physical system/subsystem as part of the design process is dependent on technological and economical context etc.. It is however important to have a basis information generally operative independent of variations in this context.

In the design process it will be necessary to group the physical properties in accordance with the basic elements in a chosen physical system. Here the basic steps in our analysis are shown in Figure 3 as a summing up.

FIG. 1 ESTABLISHING OF THE BASIC FUNCTIONS FOR BUILDINGS

THE ENVIRONMENT, OF WHICH THE BUILDING IS A PART, HAS THE FOLLOWING FUNCTIONS:

AS A SOURCE

AS A FILTER

AS AN ENCLOSURE

MAN ALSO NEEDS SERVICES FOR HIS SUPPLY AND WASTE.

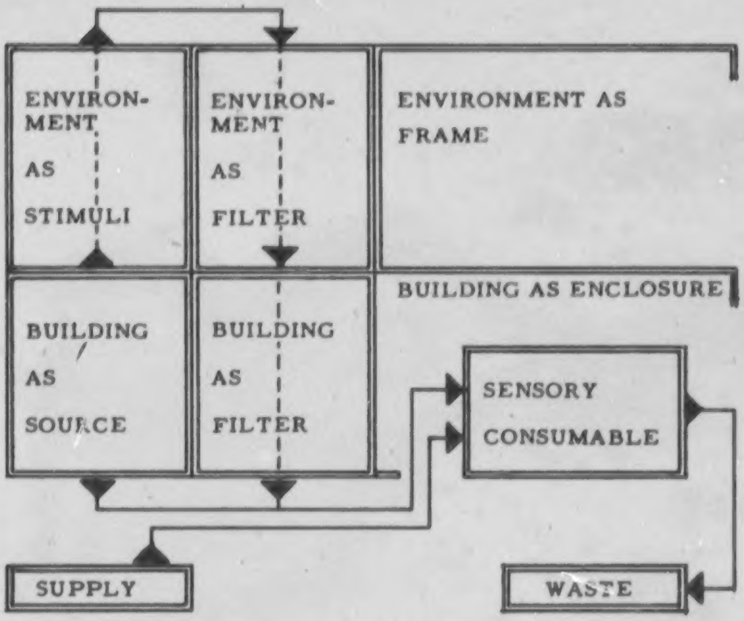
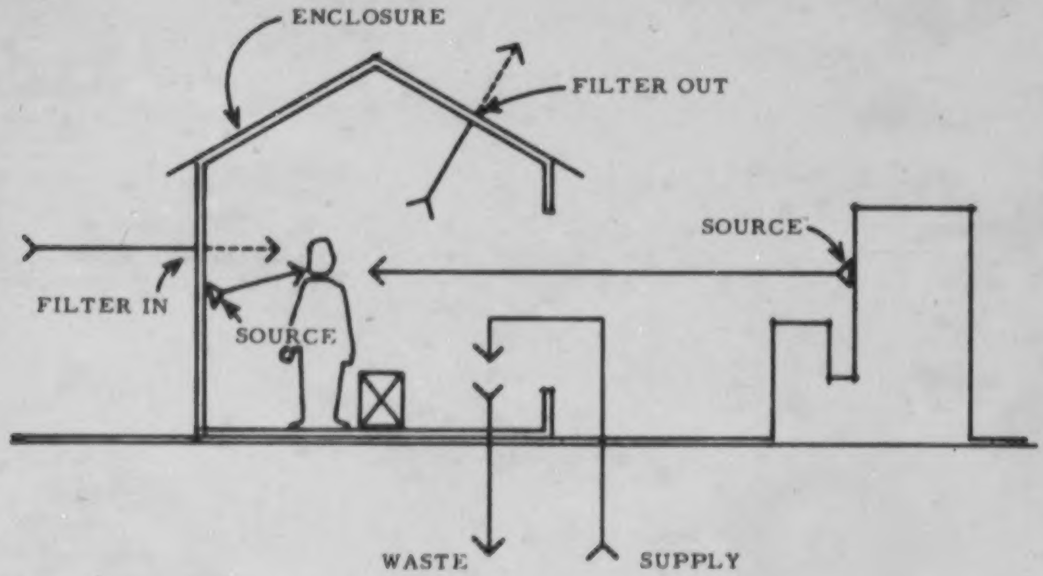

ENVIRONMENT AS STIMULI
ENVIRONMENT AS FILTER
ENVIRONMENT AS FRAME
BUILDING AS ENCLOSURE
BUILDING AS SOURCE
BUILDING AS FILTER
SENSORY
CONSUMABLE
SUPPLY
WASTE

FIG. 2 OUTLINE OF FRAMEWORK FOR STRUCTURING REQUIREMENTS


ENCLOSURE
FILTER OUT
SOURCE
FILTER IN
SOURCE
WASTE
SUPPLY

THIS DRAWING IS A SIMPLE EXPLANATION OF THE BASIC FUNCTIONS. THESE FUNCTIONS MAY BE USED IN AN ANALYSIS FOR STRUCTURING THE REQUIREMENTS AS SHOWN HERE:

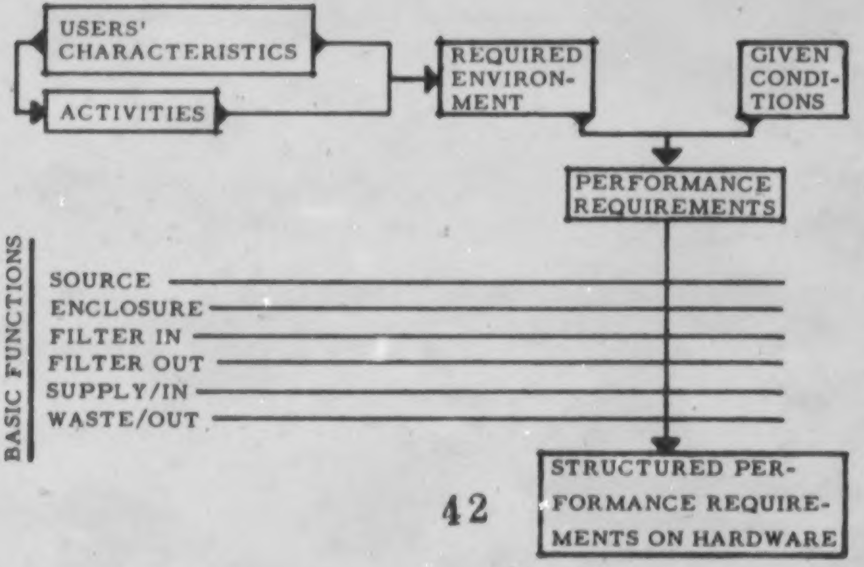

USERS' CHARACTERISTICS
ACTIVITIES
REQUIRED ENVIRON-MENT
GIVEN CONDI-TIONS
PERFORMANCE REQUIREMENTS
BASIC FUNCTIONS
SOURCE
ENCLOSURE
FILTER IN
FILTER OUT
SUPPLY/IN
WASTE/OUT
STRUCTURED PER-FORMANCE REQUIRE-MENTS ON HARDWARE

FIG. 3 OUTLINE OF A PROCEDURE

USERS' REQUIREMENTS IN PLAIN LANGUAGE - STRUCTURED ACCORDING TO:	USERS' REQUIRED CONDITIONS - STRUCTURED ACCORDING TO:	PERFORMANCE REQUIREMENTS ON THE BUILDING HARDWARE ACCORDING TO THEIR BASIC FUNCTIONS		CHOICE OF PHYSICAL SYSTEM/ SUBSYSTEM
ACCESSABILITY/ USABILITY. PERCEPTION/ COMFORT. SAFETY/ PROTECTION. SOCIAL ADJUSTABILITY	INPUT SENSORY CONSUMABLE OUTPUT SENSORY WASTE FRAME SPACE CLIMATE	SOURCE ENCLOSURE FILTER IN FILTER OUT SUPPLY/IN WASTE/OUT	PHYSICAL PROPERTIES STRUCTURED ACCORDING TO BASIC FUNCTIONS	PHYSICAL PROPERTIES STRUCTURED ACCORDING TO CHOSEN SYSTEMS.

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Performance Requirements of the Thermal Environment for Human Occupancy

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Recent physiological and psychological research is analysed from an engineering point of view to determine the ranges of the variables which provide satisfaction with the thermal environment. The preferred values of the thermal variables, dry bulb temperature, mean radiant temperature, water vapor pressure in the air and air velocity, are presented for various levels of activity and clothing. Permissible steady-state deviations are defined for practical satisfactory environmental control. The effect of variations with time is discussed and recommendations are given for limiting criteria. The environmental variations associated with different human activities and clothing ensembles are analysed.

The necessary shift in dry-bulb air temperature to maintain subjective comfort in response to variations in the other thermal parameters is presented as the suggested functional requirement and as a means for assessing the quality of existing or proposed environments. Simulation of the total building system is suggested including Man, the Building, Climate and the Environmental Control System. A man-analogue is described for use with design simulation models or for performance ratings with on-site measurements.

On analyse, du point de vue du génie civil, de récentes études physiologiques et psychologiques pour déterminer la gamme des variables qui satisfassent les conditions de l'environnement thermique. Les valeurs préférentielles des variables thermiques, température du thermomètre sec, température rayonnante moyenne, pression de vapeur d'eau dans l'air et vitesse de l'air sont présentées pour différents degrés d'activité et d'habillement. On précise les écarts admissibles en régime permanent pour un contrôle pratique satisfaisant de l'environnement. L'effet des variations dans le temps est étudié et l'on donne des recommendations pour des critères restrictifs. Les variations de milieu associées aux différentes activités humaines et aux différents ensembles de vêtements sont analysées.

Les modifications de température du thermomètre sec nécessaires pour maintenir un sentiment subjectif de confort en réponse aux variations d'autres paramètres thermiques sont présentées comme l'exigence fonctionnelle suggérée et comme moyen d'évaluer la qualité du milieu existant ou proposé. Les problèmes d'équipement sont discutés. On montre que les exigences fonctionnelles proposées sont affectées par le climat extérieur, les éléments architecturaux de la structure, le système de climatisation et ses contrôles, tous

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[2] Senior Group Manager of Engineering, Johnson Service Company, Milwaukee, Wisconsin. Formerly, Associate Director, Institute for Environmental Research.

en tant que variables en corrélation. Un modèle analogique du système de construction total est proposé comprenant l'Homme, le Bâtiment, le Climat et le Système de contrôle du milieu.

Key words: Air motion; air temperature; comfort; mean radiant temperature; performance; relative humidity; thermal environment; thermal neutrality.

1. Introduction

It is the purpose of this paper to suggest that the performance of a building environmental system must include the human occupants as part of the system and to recommend performance requirements based on human physiological and psychological responses to all factors of the thermal environment. In addition, it is shown that the evaluation of the thermal environment cannot be based on measurements of supply air temperature, supply air volume flow rate, and other physical data alone.

2. Human Requirements for Thermal Comfort

ASHRAE Standard 55-66, Thermal Comfort Conditions [1][3], defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment." An important feature of this definition is the use of "the condition of mind" as opposed to "the condition of the body." Obviously, psychological response to an environment will be determined by stimuli which effect all body senses. The occupant's physiological response is determined essentially by the thermal exchange between the occupant and the thermal parameters of the environment.

The designer must be cognizant that a human response of "comfortable" is a complex physiological and psychological reaction involving perhaps fifteen or more factors [2]. Three types of variables can be discussed, (1) physical factors, such as temperature, relative humidity, air velocity, size of the room, light field, air pressure, etc.; (2) organismic factors, those factors which the individual occupant brings into the space such as age, sex, body-type, and drive; and (3) reciprocative factors, interactions between the man and the environment, sometimes called behavioral factors, such as diet, clothing, and activity. Many of these factors have minor or even negligible effect on a person's response to the thermal environment.

The variables directly influencing thermal comfort are: 1) Physical Factors--dry-bulb temperature, water vapor pressure in the ambient air, air motion (relative air velocity), thermal radiation exchange (mean radiant temperature), and the time variations in these parameters; and 2) Reciprocative Factors--activity (heat production) and clothing (thermal insulation). Individual differences--age, diet, sex, etc.--are assumed to be second order variables and are handled by employing averages for a group of human occupants.

For an occupant to be satisfied with the thermal environment, the physical parameters must be such that the heat generated (metabolic activity) is equal to the heat lost and that the person is in a zone of thermal neutrality. It is important to note that thermal neutrality is a necessary but not a sufficient condition for comfort. For example, non-uniform effects such as a draft on the neck or ankles, or radiant loss to a cold window on one side may cause discomfort even though the spatial integration of the heat balance is neutral. To further complicate the situation, there exist significant differences between individuals and their preferences for a given set of environmental conditions. There is also a range of thermal conditions which will be satisfactory for a given individual at any given time, activity level, etc. The preferred conditions for a given individual may also vary with time and with other non-physical aspects of his environment in addition to the normal variations resulting from physiological rhythms. Fanger [3] has suggested that the maximum percentage of a significantly sized group that will express satisfaction with an environment is 95 percent. ASHRAE Standard 55-66 specifies thermal conditions which will satisfy 80 percent of the occupants for sedentary and slightly active, healthy, normally clothed people in the United States and Canada. The number of responses on a subjective voting scale will affect the modal value. Usually a seven point scale is used. With seven choices, any single thermal condition will satisfy no more than 80 percent of the individuals voting. Fewer choices would result in satisfaction for a higher percentage.

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[3] Figures in brackets indicate the literature references at end of this paper.

Table 1 summarizes the "thermal" parameters of the ASHRAE Comfort Standard 55-66. Of the seven thermal parameters mentioned above, the Standard provides limits for the five physical factors. It is applicable essentially to only one level of activity and one level of clothing (lightly clothed adults at office work activity levels). Since the Comfort Standard is intended for practical, field applications, a range for each variable is specified which permits its application to spaces which several individuals may occupy simultaneously and who may have slightly different activity levels and may be wearing clothing having slightly different values of insulation, all within some practical limit.

3. Performance Requirements

Using data from Kansas State University, the John B. Pierce Foundation Laboratory and the Laboratory of Heating and Air Conditioning at the Technical University of Denmark, specifications are suggested below for the performance requirements of the thermal environment in terms of the seven primary environmental variables which effect thermal comfort. Due to the difficulty of representing a seven-dimensional system, it is necessary to establish the gradient (rate of change) of each parameter with another and to apply each essentially independently of the others.

Since dry bulb temperature is usually the major factor in determining the thermal exchange of the human body, it has been chosen as the independent variable. Additional argument for this choice is that in most environmental control systems, the dry bulb temperature is the controlled variable, and it is the most commonly used single variable employed to estimate or classify the thermal environment. The general air motion in a given space is usually fixed at the time of the installation of the air diffusion equipment and is normally small compared to the relative air velocity caused by activity such as walking. The body heat transfer coefficients, therefore, are determined largely by the activity level of the occupants and not by the building air conditioning system. Thermal radiation exchange or the mean radiant temperature is determined by the inside surface temperatures of the space which in turn are dictated normally by the outdoor conditions, the construction of the building, window areas, solar load, etc. It should be noted that these inside surface temperatures are strongly dependent on the inside air temperature. In panel heated or cooled systems, of course, the mean radiant temperature can be a controlled parameter.

The work of Nevins et al. [4] and Rohles [5] with college-age subjects provides a baseline curve and a comfort envelope or zone of thermal neutrality for sedentary activity and lightly-clothed subjects. McNall et al. [6] give basic experimental data for three levels of activity. The specific values of the seven variables which form the baseline performance criteria for thermal comfort are shown in Table 2.

As is the case with many complex problems, the equation which relates the thermal comfort of a human occupant to the thermal parameters of the environment is non-linear. The change in dry bulb temperature necessary to compensate for a unit change in one of the other six variables is, therefore, a function of the magnitude of the variable being considered or some combination of these variables i.e., the state point from which a shift in a given variable may occur. For practical applications, and to reduce an almost infinite number of combinations of the variables to a manageable or practical number, the range and number of possible environmental situations has been limited based on engineering judgment and experience.

Relative humidity or, more appropriately, the partial pressure of the water vapor in the air has been shown to have a small effect in the zone of thermal neutrality within the range of 20 to 65 percent for sedentary subjects. For occupants involved in higher levels of activity or in warm environments, the effect of water vapor pressure increases. However, if the dry bulb temperature is maintained at the proper value to maintain thermal neutrality, the vapor pressure, if limited to 5.0 to 12.5 mm. Hg, will influence thermal comfort only slightly requiring a change in dry bulb temperature of approximately 4 to 6 F (2 to 3 C) to compensate for a change in water vapor pressure of 25.4 mm. Hg. (at 75 F (23.9 C). This is equivalent to a relative humidity change of 100%).

The influence of air motion on the zone of thermal neutrality has been studied under laboratory conditions for velocities from "still air" to 200 fpm (1.0 $m.s.^{-1}$). However, in practice air motion or relative velocity will range from 30 to 40 fpm (0.15 to 0.20 $m.s.^{-1}$) to a probable maximum of 100 to 150 fpm (0.5 to 0.76 $m.s^{-1}$) except in special cases of "spot ventilation." Thermal sensations of "comfortable" or "thermally neutral" have been achieved in the laboratory at velocities up to 200 fpm (1.0 $m.s.^{-1}$). Under these conditions the dry bulb temperature was increased approximately 8.0 F (4.5 C) to provide thermal comfort for low activity levels. Using these data and the predictive equations of Fanger [3], the change in dry bulb temperature required to offset a unit change in velocity can be estimated. It will be noted that the effect is dependent upon the level of activity and on the magnitude of the velocity about which a change in velocity occurs. The clothing insulation does not effect, materially, the rate of change of temperature with velocity.

The mean radiant temperature of an enclosure, excluding panel heated or cooled spaces, is dependent upon building construction, orientation, outdoor air conditions and solar load. The subjective data obtained by McNall [8] using sedentary and active college-age subjects dressed in light clothing, indicates that a constant condition of thermal comfort for these subjects can be achieved if the air temperature is reduced 1.0 F (0.56 C) for each 1.4 F (0.78 C) increase in mrt[3]. The space air motion was approximately 30 fpm (0.15 $m.s^{-1}$) for these tests. This recommendation was found also to be appropriate for active subjects (M/A = 36.9 Btu. hr^{-1} ft^{-2} (116.5 $W.m^{-2}$) where M = metabolic rate and A = Dubois body surface area). The relative air velocity increased to 45 fpm (0.22 $m.s^{-1}$) as a result of the increased activity level. The width of the thermally neutral zones was found to be 5.3 F (2.9 C) for sedentary subjects and 8.1 F (4.5 C) for subjects performing work with a metabolic activity of 41.0 Btu. hr^{-1} ft^{-2} (129.5 $W.m^{-2}$) for males and 37.2 Btu. hr^{-1} ft^{-2} (117.5 $W.m^{-2}$) for females. If the velocity is increased to approximately 100 fpm, (0.5 $m.s^{-1}$) a reduction of 1.0 F (0.56 C) would be compensated by an increase in mrt of 2.4 F, (1.33 C) showing again the influence of air velocity on the convection heat transfer, and the relative magnitude of the convection to radiation heat transfer.

Table 3 gives the insulation values for various commonly worn clothing ensembles. Table 4 lists the average metabolic rates for adults performing various types of common activities.

The effect of each thermal variable on the dry bulb temperature for thermal comfort is graphically illustrated in figure 1. Dry bulb temperature is plotted as the abscissa. The bars on line (1) represent the zone of thermal neutrality or the range of dry bulb temperature for thermal comfort for four levels of activity for the basic conditions given in Table 2. Line (2) indicates the shift in dry bulb temperature required to compensate for an increase in air motion of approximately 70 fpm. (0.35 $m.s^{-1}$). Line (3) shows the change in dry bulb temperature required to compensate for increases in mrt of 5 (2.8) and 10 F (5.6 C) above the neutral temperature (T_a = mrt). Line (4) shows the change in dry bulb temperature required for increases in clothing insulation of 1.0 and

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[3] This recommendation does not support ASHRAE Standard 55-66. It indicates that the air film coefficient has more influence on the heat transfer from the human body than the radiation coefficient. Standard 55-66 is currently being reevaluated in light of these and other research findings since 1966.

1.5 clo.[4] The water vapor pressure is assumed to be within 5.0 to 12.5 mm. Hg. where its effect on the dry bulb temperature would be less than 1.0 F. (0.56 C).

The values in figure 1 are estimates based on research and current practice. The range of dry bulb air temperature shown should satisfy at least 80% of the occupants of a given conditioned space if similarly clothed and engaged in similar activities. The effects, for practical purposes can be assumed to be algebraic. For example: assuming a baseline condition of:

Activity Level = $M/A = 18$ Btu. hr^{-1} ft^{-2} (56.7 $W.m^{-2}$)

Air Velocity = $V = 30$ fpm = 0.15 $m.s^{-1}$

mrt = T_a

Clothing = 0.6 clo

the dry bulb temperature for comfort would be 78 F (25.6 C). The dry bulb temperature required to compensate for an increased activity level to 38 Btu. hr^{-1} ft^{-2} (120.0 $W.m^{-2}$) would be 67 F (19.4 C). If this change in activity is accompanied by an increase in air velocity of 70 fpm ($V = 100$ fpm = 0.5 $m.s^{-1}$), an increase in temperature of 4 F (2.2 C) is required (see line 2, figure 1). The alegebraic sum of the changes then results in an air temperature for comfort of $78 - 11 + 4 = 71$ F (21.6 C).

To illustrate the use of figure 1 when changes from the baseline conditions occur for all factors, assume the following conditions:

Activity Level = $M/A = 38$ Btu. $hr.^{-1}$ ft^{-2} (120.0 $W.m^{-2}$)

Air Velocity = $V = 100$ fpm 0.5 $m.s^{-1}$

mrt = $T_{ab} + 10$ F (T_{ab} = baseline dbt = mrt)

Clothing = 1.0 clo

Then the dry bulb temperature for comfort is:

$$T_a = T_{ab} - \Delta T_{ACT} + \Delta T_V - \Delta T_{MRT} - \Delta T_{Clo}$$

$$T_a = 78 - 11 + 4 - 7 - 10 = 54 \text{ F } (12.2 \text{ C})$$

where T_a = dry bulb air temperature,

T_{ab} = baseline air temperature, = mrt (line 1, figure 1)

ΔT_{ACT} = Change in dbt for activity, (line 1, figure 1)

ΔT_V = Change in dbt for velocity, (line 2, figure 1)

ΔT_{mrt} = Change in dbt for Mean Radiant Temperature, (line 3, figure 1)

ΔT_{clo} = Change in dbt for clothing insulation, (line 4, figure 1)

4. Variation of Variables with Time

ASHRAE Standard 55-66 specifies acceptable limits for the magnitude and rate of fluctuation of temperature and relative humidity. Using college-age subjects, Sprague and McNall [9] obtained experimental data which established the limits shown in figure 2 for (a) dry bulb temperature and (b) relative humidity. As shown in figure 2(a), the amplitude limit of the temperature variation is a function of the cycle time so a peak to peak variation of 4.0 F (2.2 C) is allowable if the period is greater than 1.0 hours. However, if the period is 15 minutes, the maximum allowable peak to peak value is 2.0 F (1.1 C). From Figure 2(b), the corresponding maximum peak to peak values of relative humidity (KSU uniform) are 12% for 15 min. periods and 18% for 1.0 hr periods. With light suits the value is 22% for both 15 and 60 min. periods. The specifications of AASRAE 55-66 are shown for comparison. In general, 55-66 is conservative but acceptable. Time fluctuations in the relative humidity greater than those specified by the ASHRAE Standard may not be objectionable but the range and extent of the test conditions used by Sprague were not sufficient to justify a change in these limits. Figure 2(b) also shows the effect of two clothing ensembles on the acceptable limits of relative humidity fluctuations. Moisture adsorption and desorption in the clothing causes a heat gain or loss, respectively, which effects comfort with changing humidity.

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[4] One clo unit is 0.88 F. ft^2 hr. Btu^{-1} (0.155 C m^2W^{-1})

The possible non-uniform thermal environment referred to earlier may also be a cause of discomfort, even though the criteria outlined above are satisfied on the basis of an integrated average for the total environment. Some research has been performed in this area [10], [11], and although the results are incomplete, the evidence supports the conclusion that most practical controlled environments do not produce non-uniform thermal effects of sufficient magnitude to be of themselves, sources of discomfort. This complex effect, if ignored, should not cause serious difficulties in applying the recommended performance criteria to practical cases.

Another variable to be considered is the location of the occupants within the space. If an occupied zone is defined, for example, as in ASHRAE Standard 55-66 "3 in. (0.07 m) above the floor to the 72-in. (1.83 m) level and 2 ft. (0.61 m) from the walls, windows and fixed HVAC equipment", it is unlikely that practical environments will cause significant discomfort due to variations of position within the occupied zone. For practical purposes the above two complications are considered second order effects.

Figures 1 and 2 are then suggested as practical performance specifications to assess the acceptability of controlled environmental systems. No consideration has been given to the methods for accomplishing this performance. There exists a large number of different combinations of the various components which comprise the system which could conceivably give acceptable performance. The components are typically:

1. The building construction details
2. The microclimate surrounding the building
3. The heating and air-conditioning system and its energy source
4. The control of the HVAC system
5. The use of the building, from the viewpoint of the human occupants

The architect and engineer are completely free of restrictions on their innovative ability to provide acceptable performance and the optimum system which will satisfy the specific and unique situations surrounding each building project. The client would then be assured of acceptable system performance regardless of the specific components chosen, and there could be a greater premium placed upon economical solutions and conservation of resources.

5. System Rating

With the information generated above, the performance of the system, its ability to adjust or maintain the thermal variables to achieve thermal comfort, can be determined. An analogue of the "comfort" criteria which might be used for performance evaluation and rating is given in figure 3. The inputs to the model would be the outputs of a building-space-equipment simulation model or actual on-site measurements. Each variable is compared to a "baseline" or set-point value. Deviations from the "baseline" value are compensated by changes in air temperature according to the established transfer functions. The individual outputs are summed, algeraically, to provide the value of air temperature for thermal comfort. This value can then be compared with the air temperature in the space to provide (1) a "rating" of the system or (2) a control signal for bringing the system to the desired conditions.

6. Conclusion

Performance requirements in terms of dry bulb temperature for thermal comfort are defined for use in the evaluation of the total building system. Incorporating these criteria (the comfort analogue) into computer simulation programs, the system can be "rated" for design purposes or used for economic analysis. Using field measurements of the thermal variables, the performance of an existing structure can be determined. The proposed requirements are estimated from research data, field practice and experience. Further refinements are needed to more accurately formulate the functional relationships between the thermal variables and the building-space-conditioning equipment and control system.

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Table 1. Summary of ASHRAE Comfort Standard 55-66*

Dry-bulb temperatures (dbt)at all times	73-77 F (22.8 - 25 C)
Mean radiant temperature (mrt) at all times	70-80 F (21.5 - 26.6 C)
If mean radiant temperature is not equal to dbt, + 1.0 F (0.56 C) difference in mrt is to be offset by -1.4 F (0.78 C) in dbt and vice versa.	
Relative humidity (rh) at all times	20-60%
Air velocity (relative to the human subject)	10-45 fpm (0.05 - 0.23 $m.s.^{-1}$)
Rates of change:	
dbt's 4.0 F/hr (2.2 C. hr^{-1}) or less if Δt peak to peak is 2.0 F (1.1 C) or greater	
mrt's 3.0 F/hr (1.6 C. hr^{-1}) or less if Δt peak to peak is 1.5 F (0.8 C) or greater	
rh 20%/hr or less if Δrh peak to peak is 10% or more.	

*These conditions apply for lightly clothed adults at office work activity levels or the equivalent.

Table 2. Baseline comfort data for college-age subjects at four activity levels

Activity	Metabolic Rate, M/A Btu. hr^{-1} ft^{-2} ($W.m^{-2}$)	Air Temperatures, F (C) Males	Females	Combined
Sedentary*	18.5 (58.3)			76-80 (24-19)
Low activity**	28.0 (88.4)	64-75 (17-24)	67-75 (19-24)	
Medium activity**	37.4 (118.0)	60-73 (16-23)	63-71 (17-21)	
High activity**	47.3 (149.5)	56-68 (13-20)	57-62 (14-17)	

*rh = 25-65%, Velocity = less than 45 fpm (0.23 $m.s^{-1}$) I_{Cl} = 0.6 clo, mrt = T_a

**Water Vapor Pressure = 10.9 mm Hg.,
Velocity = less than 45 fpm (0.23 $m.s^{-1}$), I_{Cl} = 0.6 clo.

M = Metabolic rate. A = Dubois body surface area.

Table 3. Insulation values for commonly worn clothing ensembles*

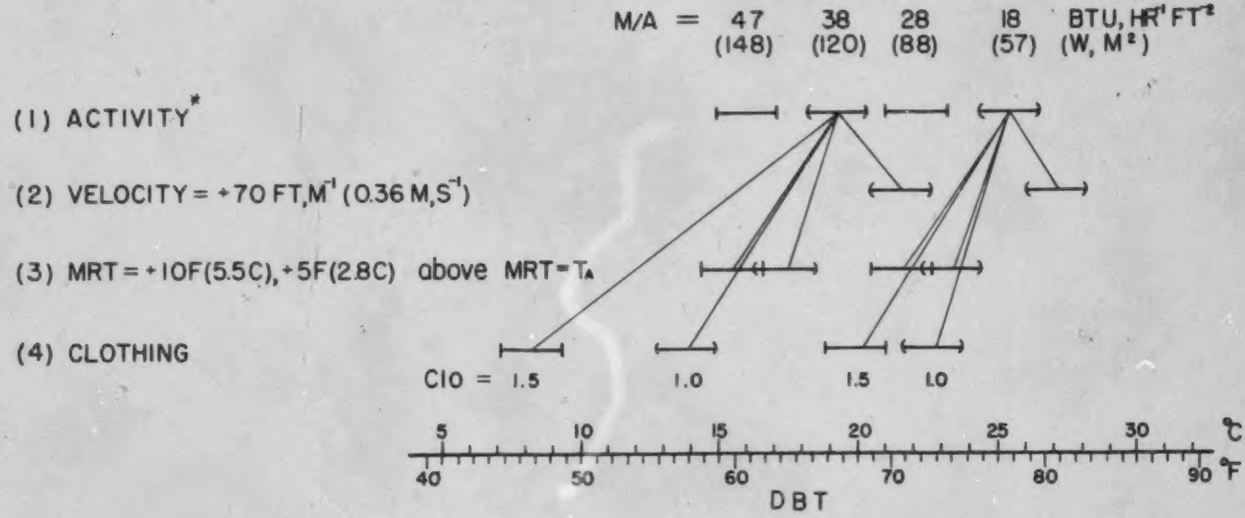
Clothing	Insulation, I_{Cl} (clo)
Shorts	0.1
Typical tropical ensemble (shorts, open-neck shirt with short sleeves, light socks and sandals)	0.3-0.4
Sweater and skirt	0.40-0.68
Blouse and skirt	0.33-0.51
Light summer ensemble (Long light-weight trousers, open-neck shirt with short sleeves)	0.50
Slacks and blouse	0.51-0.82
Light working ensemble (athletic shorts, woolen socks, cotton work shirt (open-neck), work trousers (shirt tail out)	0.6
Typical American business suit	1.0
Heavy traditional European business suit	1.5

*Seppanen, O., Minson, D. M. McNall, P. E., and Sprague, C. H., Thermal Insulating Values for Typical Clothing Ensembles, Trans. ASHRAE, 78, Part 1, 1972.

Table 4. Average metabolic rates for adults/ performing various types of activities

Activity	Metabolic Rate (M/A) Btu. hr^{-1} ft^{-2} ($W.m^{-2}$)
Seated, quiet	18.4 (58.0)
Seated, relaxed	22.1 (70.0)
Walking, on level, 2 mph	36.8 (116.2)
4 mph	70.0 (221.0)
Light Machine Work	36.8-44.2 (116-139)
Heavy Machine Work	64.5-82.8 (204-262)
Teacher	29.4 (92.8)
Car Driver	27.6 (87.0)
House Cleaning	36.8-62.5 (116-198)
Typing	22.1-25.7 (70-81)
Calisthenics	55.2-73.5 (175-232)
Social Dancing	44.2-80.8 (140-254)

M = Metabolic Rate, A = DuBois body surface area.



*DATUM: $V = 30\text{–}40\ \mathrm{FT,M^{-1}}\ (0.15\text{–}0.20\ \mathrm{M,S^{-1}})$, $MRT = T_A$, $I_{cl} = 0.5$ Clo, $P_v = 10.9$ mm,Hg

Fig. 1 Recommend Variation in Dry Bulb Air Temperature to Maintain Thermal Comfort in Response to Changes in Activity, Velocity, Mean Radiant Temperature and Clothing.

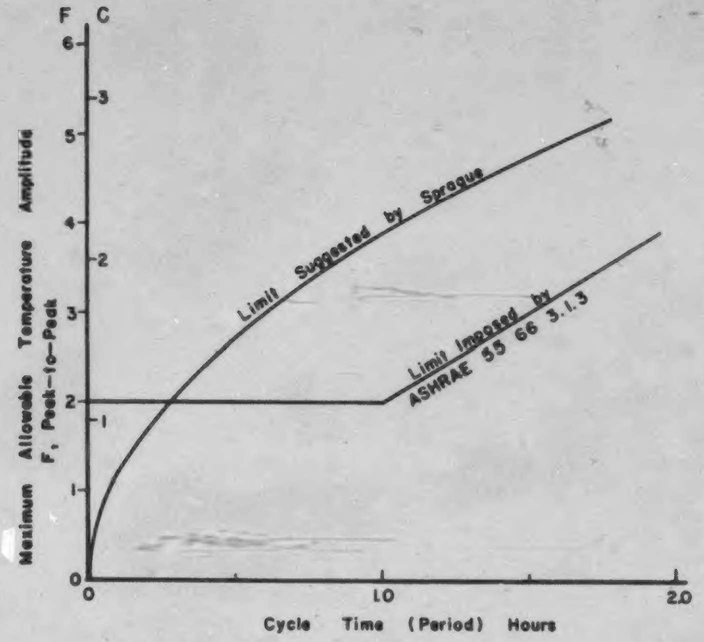


Figure 2(a) Recommend Maximum Dry Bulb Temperature Amplitude for Thermal Comfort as a Function of Cycle Time.

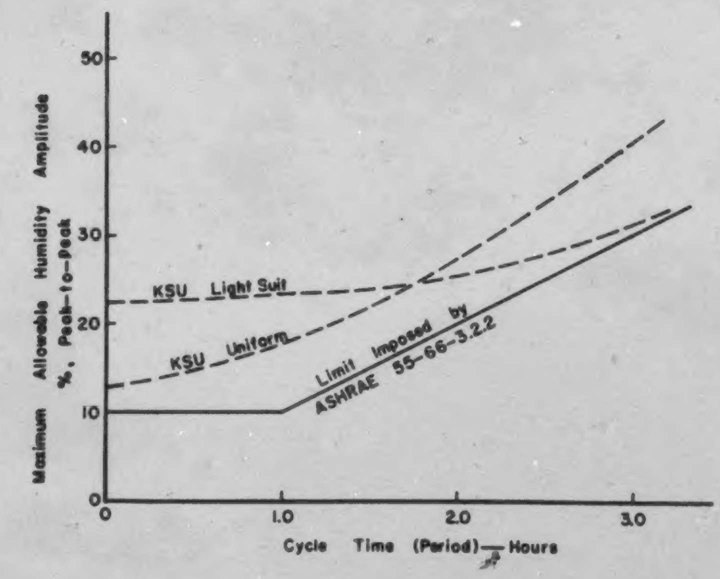


Figure 2(b) Recommend Maximum Humidity Amplitude for Thermal Comfort as a Function of Cycle Time.

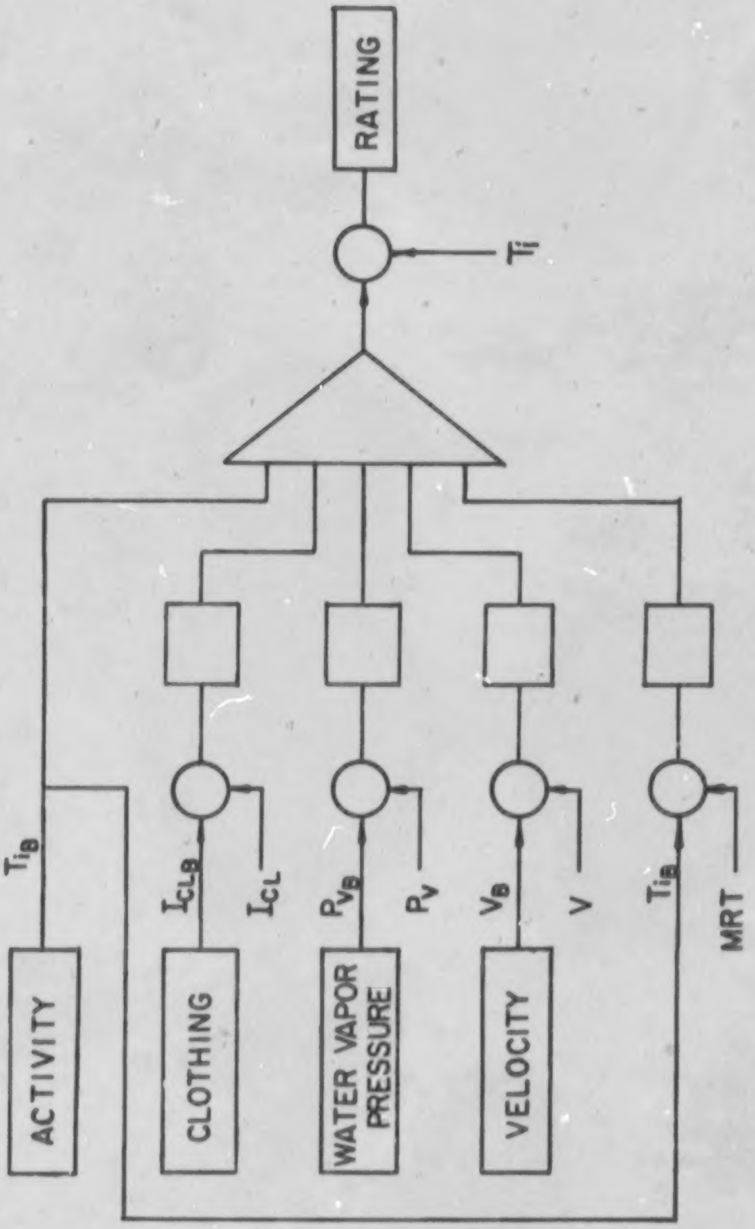

RATING
Ti
ACTIVITY
CLOTHING
WATER VAPOR PRESSURE
VELOCITY
Ti_B
I_CLB
I_CL
P_VB
P_V
V_B
V
Ti_B
MRT

Fig. 3 Man Analogue for Performance Rating.

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

Performance Requirements of Buildings and the Whole Problem

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Because so many groups of people (the client owner group, the client user group, and governmental agencies) participate in establishing performance requirements for an architectural project, the approach must be rational enough to withstand public scrutiny and analytical enough for the data to be classified and interrelated for greater mutual understanding.

Programming is a process leading to the statement of an architectural problem and the performance requirements to be met in offering a solution. Architectural programming is problem seeking, resulting in those qualitative and quantitative statements that describe the whole problem in terms of function, form, economy and time. The performance requirements deal with what is to be achieved without regard to the physical response.

The search for performance requirements is evident in each of the five steps of the programming process which follow:

1. Establish Goals (Qualitative)
2. Collect, Organize and Analyze Facts (Quantitative)
3. Uncover and Test Programmatic Concepts (Qualitative)
4. Determine Needs (Quantitative)
5. State the Problem (Qualitative)

The steps and considerations form an analytical framework for classifying and processing data (coming from many sources) into information. This framework is also useful in avoiding information clog and as a format for dialogue among the many participants.

A typical problem can involve the rote application of a hardware system without concern for the user. However, if the approach emphasizes the performance requirements of the user, then we have defined a unique problem. A hardware system may then be a part of the solution but it will be applied in the context of the whole problem.

Il est tant de groupes(le groupe du client-propriétaire, le groupe du client-usager et les agences gouvernementales) qui participent à l'élaboration d'exigences de performance d'un projet d'architecture, que l'abord doit être assez rationnel pour supporter l'examen rigoureux du public et assez analytique pour que l'apport puisse être classé et traité en termes corrélatifs, dans le but d'une compréhension mutuelle plus grande.

Par la performance, on traite qui peut être accompli sans égard aux contingences physiques. Dans ce sens, la planification architecturale est recherche de problèmes menant à ces énoncés qualitatifs qui décrivent le problème entier en termes de fonction, de forme, d'économie et de temps...... comme conditions appropriées des problèmes architecturaux.

La recherche des exigences de performance comprend une méthode analytique qui revient à:

1. établir les objectifs (qualitatif)
2. collectionner, organiser et analyser les faits (quantitatif)
3. découvrir et mettre à l'épreuve les concepts de planification (qualitatif)
4. déterminer les besoins (quantitatif)
5. formuler le problème (qualitatif)

Les différents échelons sont alternativement qualitatifs et quantitatifs. Les échelons et considérations forment un cadre analytique pour classer et traiter les renseignements(venant de nombreuses sources) en information. Ce cadre est aussi utile pour éviter l'engorgement de l'information et assurer le dialogue entre les nombreux participants.

Un problème type peut inclure l'application routinière d'un système de "hardware" sans tenir compte de l'usage. Toutefois, si la méthode d'approche souligne les demandes de l'usager, alors, nous avons défini un problème unique. Un système de "hardware" peut alors être un élément de la solution, mais il sera appliqué dans le contexte du problème entier.

Key words: Analytical procedures; architectural programming; buildings; performance requirements; problem seeking; statement of the whole problem; user needs.

1. People Participation

Many groups of people participate in the establishment of performance requirements for an architectural project. They approach the planning of a project from separate points of view. Each group can be expected to play a different role based on its set of values, on its interests and on its own perception of wants and needs and may bring with it a different hierarchy of common values or even a different set of values.

In order to emphasize the various points of view, it might be expedient to identify the groups and to

ascribe to them generalized concerns as might fit their roles as follows:

(1) The administrative group concerned with:
    (a) Reducing the time for planning and construction,
    (b) cost control if not cost reduction and
    (c) quality control

(2) The professional group represented by the designer concerned with:
    (a) The opportunity for innovation in terms of the finished building,
    (b) the inherent human values and
    (c) the visual quality.

(3) The client user group concerned with:
    (a) The hope of greater satisfaction of its needs,
    (b) knowing how these needs may be met and
    (c) occupying and testing the finished building.

(4) The client owner group concerned with cost reduction and cost control.

Each group may consist of an ever increasing number of people and may include multi-headed subgroups. Some of these subgroups can be identified as governmental agencies, special consultants, boards of directors, department chairmen, user representatives, building committees, and increasingly -- interested citizens.

2. An Organized Process

With so many different people involved in the establishment of performance requirements, the need for an organized process is indicated.

The process must be rational enough to withstand the scrutiny of so many individuals. This is particularly true in the case of government projects where there is an obligation to the community to properly allocate funds as well as to satisfy social and human values.

The process must be analytical enough to allow for the classification and interrelation of the expressions -- the wants and needs, the opinions and attitudes -- of the many participants. Analysis may provide a format for dialogue which could result in a greater mutual understanding.

Without doubt there are many procedures which, when followed, can produce the performance requirements for an architectural project. These requirements deal with what is to be achieved without regard to the physical response and can be associated with established programming procedures. This paper is based on one such organized process for programming.

3. Architectural Programming

Architectural programming can be defined as a process leading to the statement of an architectural problem and the performance requirements to be met in offering a design solution.

This definition is based on the assumption that problem solving is a valid approach to the design of buildings. Therefore, if the design is problem solving, then programming is problem seeking. The distinction between problem seeking and problem solving is central to an understanding of the total architectural process.

Essentially, programming is that analytical phase before the synthesis in many design methods. If in the synthesis phase the parts are put together in a physical solution, in the analysis phase the parts are identified and their inter-relationships understood without regard to the physical response.

It would seem obvious that in order to solve an architectural design problem, it is necessary to define and understand the problem itself.

The programming process leads to the statement of the whole problem. This statement is the link, the interface, between programming and design.

A partially stated problem is likely to result in a partial solution. This would happen when there is too little information or when not all the form-giving factors have been considered.

4. Considerations

What might these form-giving factors or considerations be? They might be those categories of information or of performance requirements which are appropriate for architectural problems.

The whole problem then serves to point up constituent problems, in terms of four considerations, those of function, form, economy and time.

The principle behind the "whole" problem is similar to that of overviewing the "whole" college examination before starting to answer individual questions. The whole problem must be uncovered and defined before starting to solve any parts of it.

If the design of a building is to solve (sub) problems of function, form and economy with time considerations, then programming must treat these as basic considerations by which to classify information.

These basic considerations can lead to the establishment of criteria for evaluating the programming package, the design solution and the finished building as well -- although different interpretations will be used for product evaluations. (Evaluation of performance is not a part of this paper.)

The brief description below of the sub-categories of the considerations are oriented to the information most appropriately useful in the programming phase. Refer to figure 1.

(1) Function deals with the relationships, the activities, and the numbers and types of people. It deals with social and functional organization.

(2) Form is used here to evoke questions regarding the physical and psychological environment to be provided, the quality of construction and the conditions of the site. The physical environment involves physical comfort needs such as illumination, heating, ventilating, air-conditioning and acoustics. The psychological environment is so closely related to the physical environment they may be considered inseparable. However, for the purpose of this paper, the psychological environment raises questions about the effect of physical space and its design on user behavior and attitudes -- considering such stimuli as form (shape), scale, proportion, space, color and texture.

(3) Economy emphasizes the need for early cost control and brings up for consideration the initial budget, the operating cost and the long-term cost which may be affected by initial quality of construction.

(4) Time brings out the factors of change and growth which affect function, form and economy. Having brought out these factors during programming, time is thereafter considered an integral part of function, form and economy.

5. Five Step Process

The search for performance requirements is evident in each of the five steps of the programming process which follow:

(1) ESTABLISH GOALS

(2) COLLECT, ORGANIZE AND ANALYZE FACTS

(3) UNCOVER AND TEST PROGRAMMATIC CONCEPTS

(4) DETERMINE NEEDS

(5) STATE THE PROBLEM

In this simple procedure the steps are alternately qualitative and quantitative.

Goals, concepts, and the problem statements are essentially qualitative, while facts and needs are essentially quantitative. For facts and needs the computer could be used as an analytical tool.

It would be good to go through the steps in sequence but in actual practice they may be concurrent -- all but the last step.

All four considerations interact simultaneously at each step of the process. Refer to figure 2. For example, the investigation of goals leads to form goals, functional goals, economy goals and time goals.

And if each of these considerations has say, three sub-categories, then it is possible to pose twelve pertinent questions regarding goals alone. A dozen questions per step can provide some sixty questions altogether.

The steps and considerations then form an orderly framework for classifying and processing data into information that comes from many sources, from many participants.

This framework is particularly useful in avoiding information clog when there are massive quantities of information.

Another way of coordinating the steps and considerations is to establish a simple matrix. This matrix can be used as a checklist for missing information and as a device to display the emphasis of information at each step. Refer to figure 3.

5.1. Step 1: Establish Goals

Goals can be classified as (1) operational goals and (2) project goals. While operational goals are concerned with the process of planning and constructing a building in terms of people, cost and time; project goals are concerned with the product in terms of function, form, economy and time -- and their sub-categories.

a. Operational Goals and Techniques

Operational goals may stem from operational decisions made by the client/architect team. The effort is to identify the best possible results in the following terms:

(1) People:
    (a) Goal to organize for effective team action
    (b) Goal to expedite decision-making

(2) Money:
    (a) Goal for expected profit on architect's fee
    (b) Goal to optimize return on client's investment through effective cash flow

(3) Time:
    (a) Goal for expected occupancy date
    (b) Goal to compress the project delivery time

Operational goals are generally a result of the architect's contract. These goals will affect how the team will proceed to fulfill the contract and may lead to techniques which would implement operational goals such as the following:

(1) The use of concurrent scheduling procedures (to compress total project delivery time)

(2) The employment of computer services to process materials delivery dates (to meet expected occupancy date)

(3) The use of systems building (to optimize return on client's investment)

While operational goals and techniques are important to the process of planning and constructing a building, the emphasis in this paper is on project goals, on the product.

b. Goals and Performance Requirements

No distinction is made here among goals, objectives, aims, purposes, intentions, aspirations and ends. All of these words are used to mean something to be attained, accomplished or achieved, toward the success of the project. Goal statements then can be viewed as those performance requirements which need to be tested during the programming process.

Policy statements may be classified in the goals category since they are intended to guide present and future decisions and are closely related to goals.

Goals may be derived from the values and beliefs of the participants and from a study of unsettled issues. The fact that some client/users are not goal oriented (as the organized building committee or the corporate client) will make their aims and objectives illusive. The information gathered may therefore be difficult to analyze and to interpret.

However, behavioral scientists are beginning to use their interview techniques and their special skills in the planning of architectural projects. In interviewing client/users they uncover the users' values, basic interests and motives which can lead to personal aims and subsequently to project goals.

Goals derived from personal aims will stress the performance expected by the eventual user and may well include the requirements to meet psychological and sociological needs.

c. Project Goals

(1) Function: Functional goals rely heavily on mission statements and on the philosophy behind the project.

Mission statements explain the reasons for the project. They answer the question "why?". They state the purpose of the organization which will guide all subordinate activities. And they will include the general functions or services to be performed without anticipating implementing concepts.

Philosophical statements can contain goal information if they are not too esoteric and not too vague to be directly useful.

Some useful key words and phrases to elicit goals might be: mission, maximum number of people to be served, human values, such as the sense of identity, priority of an activity over others, general priority of relationships, desire for efficiency, the goal for interaction versus privacy.

(2) Form: Goals on form reflect the client's attitudes toward the existing elements on the site, the desirable psychological environment to be created, the preference for high quality construction and less constructed space or for lower quality construction and more constructed space, the consideration of neighbors, and the image to be projected.

(3) Economy: Most clients have a limit to their available funds. An economy goal establishes this limit. If the limit cannot be made explicit and be evaluated, subsequent "recycling" of steps may result in drastic changes. Another economy goal may deal with the quality of construction over time which affects maintenance and operation, and in turn affects operating and long term costs.

(4) Time: Time goals may be stated in terms of anticipated change and growth.

d. Integrity of Project Goals

There is another classification of project goals which constitutes a test of their integrity:

(1) "Motherhood" goals: These are unassailable goals; however, they are too general to be useful. Example: "To provide the school with a good environment for children."

(2) Lip-Service goals: These are show-pieces that look good in a public relations publication, but upon being tested, they are found lacking in sufficient backup for accomplishment. Example: "To provide for the social development of the child" -- without ideas to accomplish it.

(3) Inspirational goals: These are general goals whose ambiguity may well serve to trigger the designer's subconcious to uncover a design concept. Example: "To project the dynamic, progressive spirit of the organization."

(4) Practical goals: These goals may provide guidance to the collection of facts. They are intended to be accomplished through programmatic concepts and may well affect the statement of the problem.

e. Congruity of Ends and Means

The integrity of practical goals is proven by the congruity of ends and means, by the reinforcement of goals through implementing concepts. The following examples might show the interrelationships among policies, issues, values, goals, facts, and concepts.

Policy: To provide for a maximum enrollment of 5000 FTE before establishing a second campus.

Issue: Whether or not a 5000 FTE campus is educationally and sociologically good.

Value: The worth of the individual as a human being.

Goal: To help maintain the individual student's sense of identity within the large mass of 5000 FTE students.

Fact: Enrollments in this college will grow from the initial 1500 to 5000 FTE students.

Concept: Decentralized social organization.

5.2. Step 2: Collect, Organize and Analyze Facts

a. Pertinent Facts

Goals can be used to determine what kinds of facts will be useful and meaningful. Yet it is necessary to discriminate between immediately useful facts which will influence schematic design and the details which will be useful at a later phase.

b. Facts and Performance Requirements

Facts may involve many numbers -- such as the number of students which generate space requirements in a school. However, facts may also involve statements of conditions presented as having objective reality; and these generate performance requirements.

c. Classification of Facts

Facts must be organized and analyzed to reveal their relative importance. The classification of facts under function, form, economy and time is a useful way of organizing and analyzing the information.

(1) Function: The space adequacy for the number of people and their activities needs to be evaluated. The analysis might include:
  (a) the physical and emotional characteristics of the people to be served,
  (b) their behavioral patterns,
  (c) the special requirements of ethnic groups, and
  (d) the characteristics of the community.

(2) Form: Classified under Form Facts might be such important information as:
  (a) the analysis of the physical and climatic characteristics of the site,
  (b) the evaluation of the form-giving significance of code requirements,
  (c) the evaluation of the soil test report and the implications on cost and design,
  (d) the understanding of the psychological implications of form.

(3) Economy: One important fact might be based on the mutual understanding by architect and client of building quality on a quantitative basis -- such as cost per square foot.

(4) Time: Facts in this category pertain to long-term functional and economic projections and the evaluation of the historical significance of neighboring buildings.

5.2. Step 3: Uncover and Test Programmatic Concepts

a. Programmatic and Design Concepts

There is a great need to understand the difference between programmatic concepts and design concepts.

Programmatic concepts refer to ideas intended mainly as functional and organizational solutions to the client's own operational problems.

On the other hand, design concepts refer to ideas intended as physical solutions to the client's architectural problems.

b. Examples

Programmatic concept: Decentralize the mass of 2,700 students into three "schools" of 900 students each.

Design concept: The physical response to the programmatic concept of decentralization above may be:

(a) The dispersion of three buildings,
(b) the dispersion/compactness of three floors in one building, or
(c) the compactness of a single building with three identifiable schools on one floor.

c. Programmatic Concepts and Performance Requirements

Programmatic concepts can be clearly identified as performance requirements since they involve what is to be achieved operationally without regard to the physical response of design concepts. The heavy emphasis on performance is a direct result of the client's active participation in the programming process. It is here that the client can display his most creative thinking. Programmatic concepts may be used to stimulate innovation in operational solutions which in turn will later stimulate innovation in architectural design solutions.

d. Recurring Programmatic Concepts

Concepts can be brought out and tested through the use of "evocative words" which may trigger useful information. These evocative words may be used to identify recurring concepts which appear as potential aspects of any project. Examples of concepts are: Flexibility, flow, centralization, integration, priority, people grouping, orientation and sense of place.

(1) Function: The following procedures might be clues to the uncovering and testing of functional concepts.

People: Uncover the physical, social and emotional characteristics of people, as individuals, in small groups and in large groups.

People: Investigate the sizes and kinds of groups to be housed -- both in the present and in the future.

People: Understand the need for humanistically sized groups.

Centralization vs. Decentralization: Understand the organizational structure and the functional relationships.

Priority: Uncover a hierarchy of activities.

Integration vs. Compartmentalization: Understand the difference between the need for interaction and the need for privacy.

Flow: Evaluate the flow charts regarding people, vehicles, services, goods and information.

(2) Form: Form concepts may be uncovered through the use of such evocative words as: orientation, sense of place and home base.

(3) Economy: The concept of multi-function needs to be evaluated against the required efficiency for each of the functions intended to be combined.

(4) Time: The concepts of convertibility and expansibility result from the need for functional change and growth to occur over time.

5.4. Step 4: Determine Needs

a. Space, Budget and Quality

The fourth step determines the feasibility of the project and it seeks to establish quantitative needs of the client in terms of space requirements, a budget (as predicted for the time of construction) and quality (as expressed by cost per square foot).

It is here that agreement must be reached on a definite space program for which funds are available. The cost estimate analysis must be as comprehensive and realistic as possible, with no doubt as to what comprises the total budget required. Refer to figure 4.

b. Needs and Performance Requirements

The proposed space requirements and the expected level of quality must be tested against the proposed budget at this step in programming. The performance requirements must now be expressed in terms of needs as being necessary and financially feasible as opposed to wants which are desirable but financially unattainable.

(1) Function: Under this classification fall the following procedures:
   (a) Establish the gross area requirements
   (b) Establish the outdoor area requirements
   (c) Understand the cost implications of functional alternatives
   (d) Evaluate the efficiency ratio or net to gross areas.

(2) Form: The following procedures help to identify the Form considerations:
   (a) Establish the quality (cost per square foot)
   (b) Consider site influences on cost
   (c) Consider factors of physical and psychological environment as influences on the construction budget.

(3) Economy: The information classified here involves the following:
   (a) Analysis of the cost estimate
   (b) Evaluation of initial and long-term costs.

(4) Time: Time considerations involve:
   (a) Evaluation of the realism of the cost escalation factor
   (b) Consideration of phasing of construction as an alternative in case of imbalance between space, quality and budget.

5.5. Step 5: State the Problem

a. Essence and Uniqueness

The statement of the problem is the link between problem definition and problem solving. The problem, stated in qualitative terms, should bring out the essence and uniqueness of the project.

The essence of the project can be found by evaluating all the information from the previous steps and by abstracting the most important statements that can be made regarding the whole problem. There should be a minimum of four statements concerning function, form, economy and time. There should be no more than ten statements in an effort to reduce the problem to the essential statements about important form givers. More than ten might indicate either that the project is very complex or that mere details are being used as premises for design. The statements must deal with the unique, not the universal aspects of the problem.

b. Problem Statements and Performance Requirements

These problem statements, or premises for design, should be made in terms of performance, so as not to close the door to different expressions in architectural form.

(1) Function: The statements regarding function state the unique performance requirements to satisfy the needs of the client/user, to accommodate the major activities and the relationship among activities. Example: "The purpose of any performing art is to communicate a thought or feeling in a real or abstract manner. The challenge is to design a building that will condition the patron to receive that communication."

(2) Form: Statements on form identify and abstract the major form-giving influences on the project emanating from the site, environment and quality. Example: "Since the structure will occupy its own city block, it should be handsome on all sides."

(3) Economy: Statements on economy deal with an attitude toward the initial budget and an understanding how this budget will influence the generalized geometry of the project. Example: "Since the million-dollar budget is merely adequate, the solution should strive for an economy of means."

(4) Time: Statements on time consider the implications of change and growth on long-range performance. Example: "The campus must grow, there should be visual unity at each stage of development."

6. Typical Problem vs. Unique Problem

The solving of a design problem is simplified if it can be defined in the familiar terms of a typical design problem for which there is a typical pre-determined solution. A typical problem can involve the rote application of a hardware system without concern for the user.

However, if the approach emphasizes the performance requirements of the user, then these define a unique problem. A hardware system may then be a part of the solution but it will be applied in the context of the whole problem.

6.1. Performance Requirements and Performance Specifications

While performance requirements are defined in this paper as those conditions which must be met by the entire architectural solution, performance specifications state the conditions which the building's hardware systems must meet.

The early use of prefabricated building components was a design solution to a very generalized and familiar problem; however, unique performance requirements could not be met with these components.

The use of prefabricated building components was in many cases a predetermined operational decision and required that the performance requirements would emphasize needs in terms of what the solution could "tolerate" and would ignore those unique needs that were beyond the capability of the solution. The preconceived solution dictated the definition of the problem.

6.2. The Use of Performance Specifications

In recent years, since the early 1960's, the design solutions resulting from advanced technology in systems building have begun to be more flexible and to provide a broader response to the performance requirements. However, from the point of view of the user there still are these pitfalls:

(1) When the user is removed from the programming process, the use of performance specifications to obtain a hardware system with which to build can result in a typical solution to what might be a unique problem -- particularly in the 2nd and 3rd application of the performance specification.

(2) If performance criteria and specifications are not re-evaluated continually, they tend to generalize performance requirements and to ignore unique needs.

(3) Meeting the hardware performance specification and cost criteria can become the primary concern; the unique user's functional requirements become secondary. Meeting user requirements then becomes a casual by-product of the building process and not the primary intent.

(4) The bureaucratic process can tend to abuse the hardware performance specification approach because it appears to simplify administrative problems in delivering facilities.

6.3. Requirements, Specifications and the Whole Problem

The performance requirements for the project are only partially considered by the hardware performance specifications. The programming process must address the broader problem definition. In this context, performance specifications become a means of defining very detailed and measurable needs. Together, the performance requirements and the hardware performance specifications provide a very strong base for a design solution to the whole problem.

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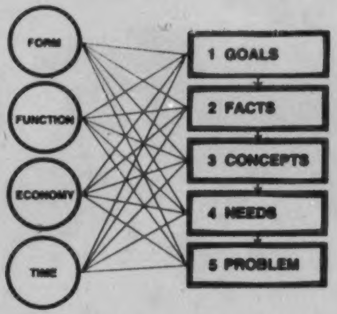
CONSIDERATIONS	
FORM	SITE ENVIRONMENT QUALITY
FUNCTION	PEOPLE ACTIVITIES RELATIONSHIPS
ECONOMY	INITIAL BUDGET OPERATING BUDGET LONG TERM BUDGET
TIME	PAST PRESENT FUTURE

Fig. 1 The information index lists information under four considerations.

Fig. 2 All considerations interact at each step.



	FORM	FUNCTION	ECONOMY	TIME
GOALS	•	•	•	•
FACTS	●	●	●	●
CONCEPTS	•	●	•	•
NEEDS	•	●	●	•
PROBLEM	●	●	●	●

Fig. 3 The matrix dots indicate a value judgement of the emphasis of information.

Fig. 4 The cost estimate analysis must account for all budget items.

COST ESTIMATE ANALYSIS

A. BUILDING COST	[illegible] S.F. at $30.00 S.F.	$6,310,000
B. FIXED EQUIPMENT	(8% of A)	504,800
C. SITE DEVELOPMENT	(20% of A)	$1,262,000
D. TOTAL CONSTRUCTION	(A B C)	$8,076,800
E. SITE ACQUISITION		300,000
F. MOVEABLE EQUIPMENT	(20% of A)	$1,262,000
G. PROFESSIONAL FEES	(6% of D)	484,600
H. CONTINGENCIES	(10% of D)	807,600
J. ADMINISTRATIVE COSTS	(1% of A)	55 700
K. TOTAL BUDGET REQUIRED	(D & E thru J)	$11,011,700

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

Performance Requirements of Housing in Response to the Life Cycle: A Behavioral Approach

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This paper concerns the development of a conceptual model dealing with performance requirements of housing in response to the changing physiological and psycho-social needs over the life cycle of the user.

The model relates the range of user needs to the human development continuum beginning with infancy and its extension to old age (100 years plus). Attention is focused on physiological and behavioral change from development in infancy and young adulthood to deterioration in old age. Changes over time in sensory acuity, energy levels, health status and activities of daily living are linked to three basic propositions regarding residential environments and user requirements: 1) The stimulus function must respond to differential sensory changes over the life cycle; 2) The orientation function of residential spaces must have high predictive value for young children and old people as well as young and middle-aged adults in order to elicit behavior appropriate to the setting; and 3) Spaces must be organized in such ways as to assure the expression of autonomy or jurisdictional control over personal space of each user while at the same time providing opportunities for social interaction with significant others.

Cette communication relate la réalisation d'un modèle conceptuel traitant les exigences de performance de l'habitation en réponse aux besoins physiologiques et psychologiques durant le cycle de vie de l'usager.

Le modèle relie la série des besoins de l'usager au développement humain continu, commençant avec l'enfance et s'étendant jusqu'à la vieillesse(100 ans et plus). L'attention se concentre sur les changements physiologiques et réactionnelles du développement pendant l'enfance et l'adolescence au déclin de la vieillesse. Les changements durant l'existence de l'acuité des sens, des degrés d'énergie, de l'état de santé et des activités de la vie journalière sont associés à 3 propositions fondamentales par rapport à l'entourage résidentiel et les demandes de l'usager: 1) La fonction stimulante doit répondre aux changements différentiels de sensation pendant le cycle de vie;2) La fonction orientatrice des espaces résidentiels doit être hautement prévisible pour les jeunes enfants comme pour les vieillards de même que pour les adultes jeunes et d'âge moyen aafin de susciter un comportement approprié au cadre; et 3) Les espaces doivent être organisés de telle façon que soit assurée l'autonomie ou le contrôle juridictionnel sur l'espace personnel de chaque usager, tout en fournissant l'occasion d'interactions sociales privilégieés.

Key words: Age and perception; complexity; home range; life cycle; life space; loss continuum; macro space; mastery; micro space; redundant cuing; sensory acuity; sensory deterioration; spatial sets; user needs.

1. Introduction

I will concentrate on old age as the part of the life cycle that perhaps best illustrates an approach which promises to enhance the relevance of design by organising spatial requirements around certain psycho-social and physiological facts of life.

Since the organism can respond directly only to those aspects of environment experienced through the sense organs, age changes in sensory and perceptual mechanisms affect very real environmental changes in the world in which the aging individual lives. Compensation for this loss in acuity is achieved either by 1) enhancing environmental stimuli so that they may be received by heightened sensory thresholds, or 2) by reducing dependence upon the affected sensory cues with consequent limitation of the range of behavior. In the latter instance, the individual learns to adjust to or live in a reduced environment as a result of his sensory decrement. In the former situation he seeks to modify the environment to make up for his deficiency.

The reduction of dependence on affected sensory cues with its attendant limitation in the range of behavior can be viewed as a reduction in life space or home range. The principle can be characterized essentially as cyclical. At infancy, life space scarcely extends beyond the body, it expands as the senses develop and reaches a maximum in adulthood where it remains relatively stable and then with old age gradually diminishes until ultimately it stops at the body once again. While it is impossible to forestall physiological losses or the reduction of home range indefinitely, it is proposed that through consciously programmed environmental stimuli and spatial hierarchies this process can be mitigated.

2. Home Range and the Human Development Continuum

Each of us has what may be described as a life space or home range. This concept is defined as a complex of familiar objects and people distributed in space with meaningful functions and relationships sensed by the perceiver. The physical dimensions and the complexity of a given person's home range is linked to his position on the development continuum. The development continuum refers to the stage of a person's lifetime physical development. At infancy, for instance, one's home range scarcely extends beyond the body. If the infant is warm and well fed and reasonably comfortable, his world literally does not extend beyond the skin. He is almost totally unaware of what is occuring around him. He is primarily concerned with his immediate environment. However, as a child develops physically and intellectually his home range begins to expand. For instance, the child begins to make sense out of his surroundings in his crib, his nursery, and so on. He begins to sort out the various arrangements of objects and spaces that he can see and relate to. Soon, as the child begins to develop an ability to walk, his home range expands even farther, going beyond the crib and nursery, out into the other rooms of the house. Before long the child is exploring not only spaces within the dwelling unit but outside as well and he begins to sort out and respond to areas immediately outside the dwelling unit. Then as he increases in age and development he continues to expand his home range until he reaches maturity, where he has almost an unlimited home range in the sense that there can be a large number of objects and people with sensed relationships that he experiences. Once the person reaches his full adult capacity, his home range is fairly stable for a long period of time until sometime in the 60's. At this point a person begins to experience a reduction in sensory acuity, health, energy levels, and activities of daily living. There is a whole series of losses that occur as a person begins to age. These losses can be sub-sumed under the human development continuum and characterized as a loss continuum (see figure 1). These losses increase in severity with each decade of life after 65 so that essentially between 75 and 85 the sensory deterioration becomes rather serious. Hearing and vision become real problems. One's other sensory modalities deteriorate as well. One's health increasingly becomes problematic. There are other losses that occur such as a diminished level of independence so that as these factors of deterioration manifest themselves with increasing severity over time, there is a reduction in one's life space or home range. Viewing the human development continuum in relation to the concept of home range, we have what might be called the rubber band principle, i.e., in infancy the home range tends not to extend much beyond the skin and as the infant develops, as his intellectual and physical development continue, the home range expands, not only in physical dimensions, but also in complexity as well. Home range hits a plateau in early adult life and remains fairly stable for a long period of time, but gradually begins to fall off as one approaches the sixth decade of life. If we extend this to the seventh, eighth, ninth, or tenth decade of life, one may literally end life in total dependence, typically bed ridden, where one's home range scarcely extends beyond the skin. So we have what might be described as the life cycle as it relates to the development of home range.

3. Environment as Language

The development and deterioration of the sensory modalities is directly related to the concept of viewing the environment as a language and one's ability to perceive and respond to environmental cues. The environment is organized every bit as intricately and systematically as any spoken language. It has a system of cues that tell us how to respond to particular situations. However, the environment communicates meaningfully only to the degree that the cues which are sent out can be received and perceived by an individual. First of all, our sensory modalities have to be developed well enough so that they can receive the signals. If, for instance, the sensory modalities such as hearing or vision are deteriorated to the point where the message cannot get through, then the person obviously cannot respond appropriately. For instance, if there is a stop sign at an intersection and an elderly person cannot perceive the stop sign as a stop sign, he is not going to respond the way he is expected to. He doesn't perceive it; thus he can't respond to it.

In response to factors regarding the developmental continuum (from physical development to deterioration and the expansion and contraction of home range) we postulate that the housing environment ought to be organized in terms of at least the following three dimensions: Organized Space as Stimulus; Organized Space as Orientation; and Organized Space as Mastery.

4. Organized Space as Stimulus

Organized space as stimulus involves the principle of getting the message across largely through stimulation. The problem is to get the visual, auditory, thermal, and olfactory messages through to the receiver. What is suggested here is a design concept called redundant cuing. Redundant cuing simply means beaming the same message through more than one sensory modality. For instance, we frequently get the message that it is winter because we can see the snow on the ground, or ice on the pond. That is a visual message, but we don't stop there. We get messages in terms of our other modalities as well. We know that it is winter because it is cold and we can feel it, we can sense the snow crunching under foot, and we can hear the wind whistling in our ears. We know that it is winter not only because we can see snow or ice, but we can also feel the low temperature, we can hear the wind and so on. The same message---it is winter---comes through in more than one modality. The principle called for is to sensorally load the environment so that the message overcomes these heightened thresholds of the elderly persons' sensory modalities. In this way the environment again becomes a meaningful language and appropriate responses to it are feasible once more.

5. Organized Space as Orientation

Organized space as orientation is a design concept which seeks to organize space for its predictive value. The idea is that, in general, a space should have a singular and unambiguous definition and use. Again, the purpose is to compensate with environmental arrangements for lessened sensory acuity. The concept has several important dimensions. In terms of orientation, the spaces are cued with landmarks which act as focal points for functionally different spaces. For example, color coded surfaces to signal functionally different spaces in terms of visual perception, textured surfaces for the tactile sense, and so on. The purpose is to sensorally load the spaces so that they may more effectively serve as points of reference. Another dimension of this concept is to organize spaces around three distinct spatial sets: personal, social, and public. It has been observed in my own research and research activities of others, that in situations where personal spaces and social spaces have been lacking and where the elderly have been forced to combine personal, social, and public spaces, friction laden encounters have occurred over the functional values assigned to space.

Spaces which denote private uses such as toileting, sleeping, certain medical procedures plus other activities such as reading, thinking, letter writing or just plain withdrawing from others to do things alone, should be distinctly bounded. Spaces for social and public uses should be similarly treated. These spatial sets with distinct boundaries not only provide options for the different functions at any given time but also signal the appropriate uses of each set and provide a contextual relationship between and among these sets.

6. Organized Space as Mastery

Organized space as mastery is a concept with at least two important dimensions. The first has to do with designing spaces which facilitate individuals with reduced abilities to claim and defend such spaces as their own inviolate spheres. This would be equally true for young children, elderly and others that may for one reason or another be vulnerable. The idea is to make it as difficult as possible for staff personnel (if institutional) or family (if home) to presume a form of spatial deprivation. Studies have shown that where persons have actually suffered a loss of control over their personal spaces they have undergone seriously destructive personality changes. Possession of a tangible piece of space seems almost essential for one's identity.

The other dimension has to do with scale and mastery. Scale in this case refers to numbers of people and size in terms of spatial dimensions. The loss continuum indicates that with increasing age an individual's world shrinks so that over time one's ability or willingness to master relationships with larger numbers of people and/or larger or more complex spaces decreases.

7. Macro-Environment

Basically, as one moves across the continuum from less severe to more severe losses, the more crucial the concepts become. The applicability of these concepts range from the micro-level of the dwelling unit to the macro-level of the neighborhood, community and beyond. Accessibility to services and support systems such as shopping, transportation church, friends, family, safety, etc., are of prime importance in terms of the macro level. Space and scale in terms of mastery are also applicable here. The scale of a neighborhood that a person typically has to relate to frequently is too large and complex for vulnerable populations with reduced capacities. In other words, a scale that may be well-suited for the mature, fully functioning adult may not be well-suited for a young child or an elderly person.

8. Micro-Environment

The micro level primarily involves enclosed spaces within the dwelling unit. Here we are concerned with stimulus factors including the whole area of lighting, textures, acoustical balance, density, and overcrowding. Spaces must be organzied in terms of an intelligent orchestration of these various dimensions if the built environment is to be fully supportive for this special population.

In terms of orientation, there is need to organise personal, social and public spaces in relation to the concept of prediction of space use; we must eliminate ambiguity from conflicting definitions and uses of personal, social or public spaces.

Lastly, we must assure the individual control over an inviolate space (personal space)--a space that others may not presume to deprive him of must be a part of the environmental design.

9. Conclusion

What has been discussed here is an attempt to identify some of the parameters associated with designing housing environments in relation to the life cycle. Much of the discussion has centered on the last half of the life cycle because that is the area where most of my research has been focused. While many of the concepts advanced in this paper are essentially propositions to be further tested, it seems that they are compelling enough to warrant serious consideration by others. What is suggested here is an approach that will enhance the relevance of design by organising spatial requirements around certain psycho-social and physiological facts of life. We must recognise, for instance, that an 80 year old person cannot handle the same level of environmental complexity as a 25 year old; that sensory deterioration can be compensated for with properly intensified and orchestrated stimuli; that life space or home range is largely a function of one's position on the human development continuum, and that this position has a lot to do with the types and amounts of space needed; that greater attention should be given to using sensory modalities other than vision and audition in more effectively cuing designed spaces; that level of mastery in terms of scale seems to be age related and should be accounted for in terms of design; that the very young and the very old spend most of their days within their dwelling units; and that thought must be given to what needs to be compensated for in the total environment because of these limitations.

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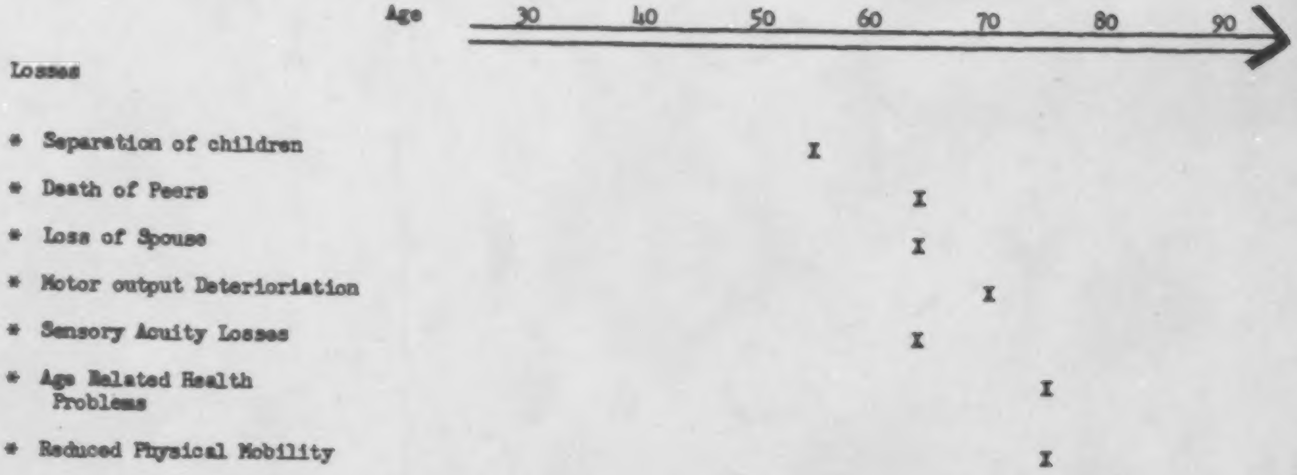
Figure 1

"The Age-Loss Continuum"



(Pastalan and Carson, Spatial Behavior of Older People, p. 98)

* The losses for each specific individual of course would not happen as precisely as indicated for each age category. This is an abstraction used for analytical purposes only.

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PERFORMANCE OF SYSTEMS OF CONSTRUCTED FACILITIES

by

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The performance of a constructed facility must be evaluated in terms of the facility's role within the larger social-economic-political system of which it is part. It is suggested that performance may be measured in terms of three principal parameters: serviceability, reliability, and maintainability. Serviceability is the degree to which the facility provides satisfactory service to the user, here understood to include a broad range of the recipients of benefits of the facility. Reliability is the probability that service will be adequate throughout the design service life of the facility. Maintainability is a measure of the degree to which continuing effort is required during the service life to keep serviceability at an acceptable level. This approach emphasises the user as a basis for evaluation, and the need to consider the entire service lifetime of a facility in decision. The implementation of procedures to permit usage of these parameters in decision-making requires application of techniques from psychology and economics, and from probability theory.

Il faut évaluer la performance des réseaux raccordés, en termes de rôle du réseau à l'intérieur du système social, politique et économique dont il fait partie. On propose que la performance soit mesurée en termes de 3 principaux paramètres: capacité de service, fiabilité et aptitude à la maintenance. La capacité de service est le degré satisfaisant de service fourni par l'installation à l'usager, et par ce dernier on entend une large série de bénéficiaires de l'installation. La fiabilité est la probabilité que le service rendu sera adéquat pour toute la durée de l'installation prévue par le projet. L'aptitude à la maintenance est la mesure du degré d'effort continuel demandé pendant la durée du service pour maintenir ce service à un niveau acceptable. Cette attitude met l'accent sur l'usager comme base d'évaluation et sur le besoin de considérer la durée totale de service d'une installation à choisir. La communication décrit ces paramètres et leur utilisation et suggère des techniques pour leur application. Les méthodes proposées permettant l'usage de ces paramètres pour la prise de décisions utilisent les techniques de psychologie et des sciences économiques de même que la théorie des probabilités.

Key words: Maintainability; measures of effectiveness; multidimensional decisions; reliability; subjective evaluation.

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1. Introduction

Systems of constructed facilities - highways, bridges, office buildings, houses, etc. - are physical units which must be planned, designed, built, operated, and maintained, subject to complex and often far-reaching interaction with the social, political, ecological and economic systems which they serve. These physical units with their typically large size and long service lifetimes, represent major commitments, not only in the conventional economic terms of capital, but also in terms of future social and political possibilities.

Resources are required for constructed facilities; commitments are made through allocations of resources to particular activities. These particular activities - undertaken as construction, operation, and maintenance - in turn determine the form of the facility and the manner of its creation, and thus the manner in which the facility provides the services for which it is intended. For example, the selection of concrete or steel structure and the manner of erection, the selection and installation of mechanical systems, the frequency of inspection, size of parts inventories, etc., may influence how satisfactory a high rise apartment building is for its residents.

Design decisions include the problems of accomodating activities, and allocating resources. Decisions are made through comparison of an action's anticipated performance and its costs. Costs are the evaluation of resource requirements for an action, while in-use performance is an evaluation of service. It may in fact be suggested that the goal of design decisions is to provide a facility which will exhibit qualities of satisfactory performance throughout its design service life, in an efficient manner. Efficiency is a relative term, comparing the level of performance achieved with a given magnitude and distribution of resources, by any particular facility configuration, with the level achieved through other possible configurations using the same resources. Thus, at any given level of resource usage the achievement of the best performance possible is a design objective.

It is necessary then to have an operational definition of performance and tools for implementation of this definition. This paper is intended to explain and illustrate a concept of performance as a decision variable for systems of constructed facilities.

1.1. Performance Defined

The central point of the concept of performance to be presented here is that the purpose of the facility is to provide service to the user, where the term user is broadly defined, representing the active components of social, political, and economic systems with which the physical system interacts (1).[1] Pursuing this line of reasoning, it may be argued that the facility may be viewed as an economic production process, i.e., supplying service to users, subject to user behavior as characterized in demand. Satisfaction of demand (the user) is then another test of the goal of selected design decisions.

Demand may be represented as a function of the price and quality of service. Setting quality of service is the concern of design decisions, and its inclusion in the demand function is often proposed by economists but seldom undertaken (see References 2 and 3, for example). Where Q is the quality of service demanded,

$$Q = Q(P,y),$$

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[1] See literature references at end of this paper.

with P and y referring to price and service characteristics respectively. The average cost of a particular facility is a function of level of usage and characteristics of service, so

$$c = c(Q,y)$$

On the principle that society receives the greatest benefit when all goods and services are priced at their true cost, it may be argued that efficiency, as mentioned previously, becomes a case of profit maximization, where profit is given as

$$\pi = P\, Q(P,y) - Q\, c(Q,y)$$

All functions are assumed to be continuous and differentiable.

Taking partial derivatives of the profit function and with some substitution, it may be shown that profit maximization occurs when the following condition is met:

$$\frac{\partial S}{\partial y} = \eta\, K\, \frac{c}{P}$$

η is the price elasticity of demand, a standard quantity in economic demand analysis, giving the change in demand relative to a change in price. K is defined as

$$K = \frac{\partial c}{\partial y}\, \frac{1}{c},$$

the fractional change in average cost in response to a change in physical qualities of service.

S is defined as the serviceability of the constructed facility. Serviceability is a measure of the degree to which adequate service is provided to users, and is evaluated as the fraction of potential users likely to find the facility's service to be adequate. That is, as a design variable, $S = S(y)$. Serviceability is then a component of performance, and is estimated through application of techniques derived in psychology and economics, based upon concepts of utility theory. (1,6)

The above argument is based upon assumptions of a single unit of time and of certain knowledge of future characteristics of service. However, adequate service must be provided throughout the design service life of a facility, so behavior must be predicted. Such predictions are essentially uncertain. These uncertainties are generally neglected or obscured through such devices as single number safety factors. It is proposed here that uncertainties must be explicitly recognized in decision if adequate service is to be delivered. Reliability is thus presented as a second component of performance.

Reliability is the probability that service will remain adequate throughout a facility's design service life, that no premature failure will occur. That is $R(t) = \text{Prob}\ [S > S_f]$, $t < \tau < T_D$, where t is the present time, T_D is the end of the design service life, and S_f is the minimum acceptable conditions of serviceability, the failure level. The condition $S > S_f$ permits definition of a set of service conditions y^*, such that $S(y^*) \leq S_f$, which denote failure in design terms.

These conditions may in turn be translated into measurable attributes of the facility, $y^* = B(X^*)$. For example, comfort in a housing unit (associated with user satisfaction) may be predicted as a function of effective temperature (y), which in turn is a function B of temperature and humidity (X). Various types of engineering models will then permit prediction of these measurable attributes as a function of service loads (for example, climate conditions) and the system's ability to resist those loads (insulation and heating equipment). This prediction is made in a probabilistic manner, permitting estimation of reliability at desired levels.

The final component of performance proposed here is intended to give explicit consideration to the timing of activities, to the opportunities for modifying decisions throughout the design service life. Maintainability is a measure of the degree to which continued action is required throughout the design service life to assure that service is adequate. The broadest class of such action is termed maintenance.

The key to evaluation lies in the idea that if these actions are truly effective and necessary, their neglect will be expected to lead to loss of a portion of the facility's design service life through the occurrence of premature failure. The measure of maintainability is the inverse of the expected value of this time lost as a fraction of the design service life.

It may be seen that reliability and maintainability are closely related, (the attribute indicator: life cycle cost) as there will be a direct correlation between the probability that failure will occur before the end of the design service life and the expected time at which a failure will occur. Taken together, reliability and maintainability provide a measure of the availability of a facility's services in the future. For maintainability is in effect the expected fraction of time lost, conditional upon the occurrence of failure, which in turn is associated with the probability 1-R.

Performance is then described in economic terms of three components: serviceability, reliability, and maintainability. Together, these three components provide an evaluation of a facility's current qualities of service and of the likelihood that this service will be adequate throughout the remainder of the design service life. These three components will now be examined in more detail, with emphasis placed upon means for their implementation.

1.2. Prediction and Evaluation of Economic Performance of a System

Serviceability has been described as a measure of the degree to which a facility provides satisfactory service to users. It will in general be a multidimensional function, reflecting the varied factors upon which the users' judgement will depend. In practice, serviceability will be characterized by a set of component subscales, each stating the fraction of users likely to be satisfied as a function of parameters, termed indicants, serving as proxies for the actual judgemental factors. Essentially, there are three steps in the process of obtaining the serviceability function. First one must identify the factors which the user considers in making judgement, the subscales of serviceability. Then, one must find suitable indicants of users' response on these subscales. Finally, the actual scaling of serviceability as a function of these indicants must be made. Identification of component subscales may be undertaken through interviews of prospective users, literature surveys, introspection, etc. An effort must be made to compress all of the myriad considerations pertinent to judgement of a facility into the essential descriptive subscales of judgement. This effort may be assisted by computerized techniques for finding problem structure (see for example Alexander & Manheim (4)). Figure 1 suggests subscales of serviceability for urban housing.

When component subscales have been identified, suitable indicants must be found to permit measurement. For example, climatic comfort in housing may be predicted on the basis of effective temperature, a parameter combining the effects of temperature and humidity. One may then proceed to develop the subscales of serviceability as a function of these indicants.

For subscales which depend primarily on subjective judgement by direct users, the scaling may be undertaken by means of psychometric methods such as are reviewed by Thurstone (5). Potential users may be asked to rate their response and to indicate preference to particular service conditions in contrast to others. Examining a number of individuals in this way, a statistical sample is built up, permitting an estimation of the serviceability function, on the single subscale. Figure 2 presents such a subscale for physical comfort as a function of effective temperature.

In more objective situations, for example the structural integrity of a building, the scaling may be done as an exercise in judgement. The range of possible loads on the structure are estimated, with the likelihood of their occurrence. Arranging these loads into a cumulative probability distribution, the form of a serviceability function is derived.

Of course, using techniques such as those discussed above require repetition for each component subscale of serviceability. A quite promising approach, as yet untested, may possibly be adapted from an advanced technique for market research (6). This technique permits the simultaneous extraction of components and a serviceability function relative to these components, using simple preference ordering data. That is, individuals are asked to compare alternative service situations, without conscious regard to the particular judgement factors that might be involved, and indicate preferences. Computer algorithms are now available to analyze these data, in a manner similar to factor analysis, for the variables required to predict the indicated preference orderings. Statistical methods may then be used to find physical qualities of the facilities which correlate closely with the prediction variables found, and thus may be used as indicants of serviceability.

In all cases, serviceability is predicted assuming that the physical characteristics of service are known with certainty. Such is not the case however, and modification must be made for the uncertainties inherent in the physical system. Hence reliability is introduced as a component of performance.

Two basic approaches to the estimation of reliability for constructed facilities may be identified. The first of these might be referred to as an analytical approach. In this case, one has definite mathematical statements relating service demands placed on the system to resistance of the system to these demands, for each possible failure mode, as a function of appropriate loads and system characteristics. A major advantage of such an approach is that one can explore relations among variables in an orderly manner, and so perhaps devise functional design methods.

The second approach might be termed an activities approach. One will try to describe the chain of events which occur, leading eventually to observation of failure in a particular mode. This approach may be used when analytical models are not available, and represents an application of a statistical view of failure. That is, it is not necessary to know why failure occurs, simply that when certain conditions are observed, failure may soon follow.

These two approaches may of course be used jointly, either in series or parallel application. In series, an analytical model may be applicable until some limit is reached, at which point probabilities are predicted by an activities model. For example, an elastic model may prove adequate for predicting deformation in the floor of a building, until a crack occurs. A parallel application may be warranted when there is more than one physical process through which a particular failure mode may occur.

In practice, the analytical approach will often be followed through application of the techniques of Monte Carlo simulation (7). The input variables for the analytical model are stated in terms of statistical distributions of their values. By means of computerized "experiments" (computerization is, of course, not required but is quite helpful), samples are drawn from these distributions and the output of the model computed. Given a sufficient number of such experimental samples, a statistically valid estimate of the distribution of output is produced. This output distribution may then be used to estimate the probability of failure in the particular mode in question.

A computationally convenient and often quite reasonable means of following an activities approach is found in the Markov process. The chain of events leading up to a failure in re-cast into a state space. A state is a description of the condition of the facility in terms of appropriate qualities and such historical data as may be required to predict future behavior (8). A collection of all possible states comprises the state space. For example, a properly working heater and exterior temperature in the range of 10°F to 30°F might be one state description in a model investigating physiological comfort in housing.

The special characteristic of a Markov process is that all that is needed to predict future states of the system is a knowledge of the current state. That is, one does not need to know how the present state was reached. For example, if one can predict the likelihood that a house will become dilapidated in five years, given that certain conditions are now observed regardless of how or in what length of time these conditions occurred, then the aging of the house may be representable as a Markov process.

Through the use of such approaches to the stochastic prediction of lifetime behavior of the constructed facility, one may compute estimates of the probability of occurrence of various modes of failure, and thus the probability of their non-occurrence, which is the system's reliability. Closely related to this parameter is the third component of performance, maintainability. As explained, maintainability is defined relative to the design service life of the constructed facility. Measures of maintainability may be stated in terms of a fraction of the service life to be lost.

If an unexpected failure occurs, a certain amount of time will be lost, depending upon the seriousness of the failure and the provisions for repair. To the extent that normal maintenance is effective, its neglect would be expected to lead to a premature failure, with a similar associated time lost from the design life. The basic measure of maintenance is then proposed as a ratio of the design service life to the possible time lost in normal maintenance and repair maintenance situations. The coefficient of maintainability so defined may be understood as an estimate of the number of times a facility could fail before the design service life would be exhausted.

1.3. Example of Service Life Prediction

Figure 3 shows the trend of serviceability as a function of time which might be expected for urban housing. Such a trend is representative of the phenomenon observed in housing, termed filtering (9).

In filtering, a housing unit which starts its service life as high quality, high income housing will, with time, lose some attractiveness. It will depreciate to become middle income housing. With additional time, the housing moves to lower income and perhaps to slum conditions. That is, losses of serviceability on particular component scales will imply dissatisfaction among a particular, identifiable faction of the potential users. In typical urban settings, each of the three use levels spans a time period of 20 to 50 years, giving housing a total life of on the order of 100 years (10).

Examination of such statistics leads one to a preliminary conclusion that as housing is designed, the early resident has a highly reliable and grossly overdesigned system.

The definition of usage levels and failure levels presents questions which will require some careful thought. The modeling of lifetime behavior and computation of reliability and maintainability may be carried out in a multistage manner, handled separately for each defined level of usage. It might be found desirable to design houses like autos, to be discarded after some particular average service life. These and similar problems must be faced in modeling the lifetime behavior of this system.

2. Conclusion

A conceptual structure and operational approaches have been presented to describe a user-based economic concept of performance for constructed facilities. Performance, a term referring to the manner in which a facility fulfills its goals in relation to the social, political, and economic systems which it serves is characterized by three components - serviceability, reliability, and maintainability. Together, these components given an evaluation of the present qualities of service and the likelihood that service will remain adequate throughout the facility's design life.

This concept of performance has been implemented for the case of highways (1, 11), and although work remains to be done in this area, the results suggest the practicality of these ideas. The example presented here, urban housing, has not been carried out so far, but it too shows promise. It would seem that further work in this area would be of great value by permitting, and indeed encouraging a working understanding of the influence of constructed facilities upon their users and thus upon society.

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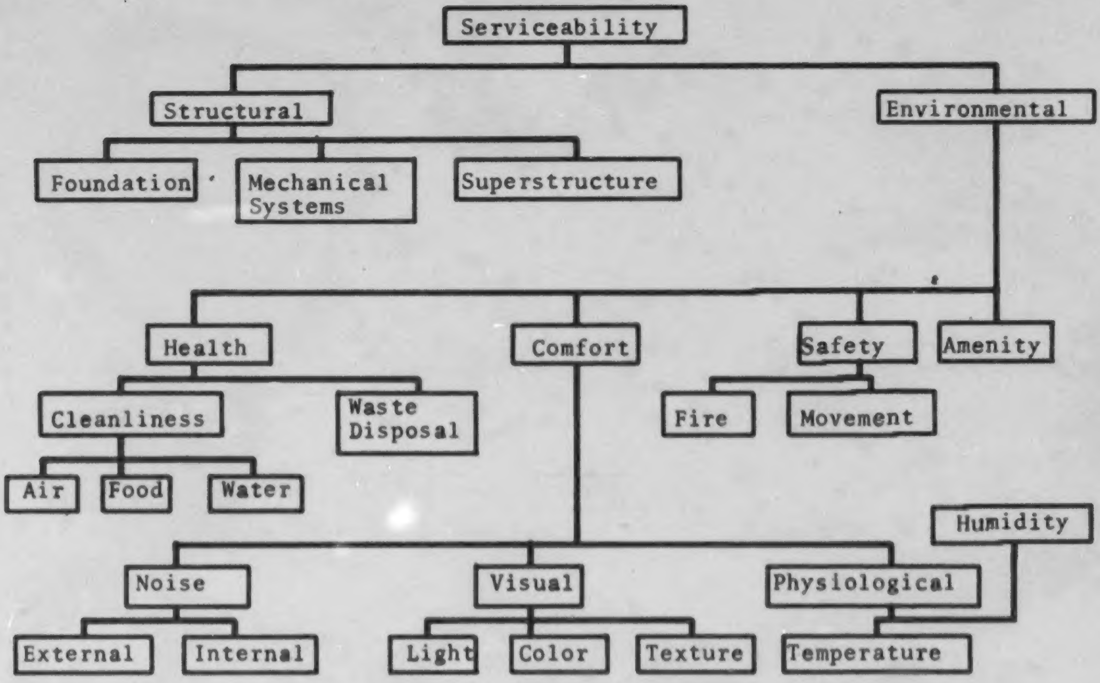
Serviceability
Structural
Environmental
Foundation
Mechanical Systems
Superstructure
Health
Comfort
Safety
Amenity
Cleanliness
Waste Disposal
Fire
Movement
Air
Food
Water
Humidity
Noise
Visual
Physiological
External
Internal
Light
Color
Texture
Temperature

Figure 1. Serviceability for Urban Housing

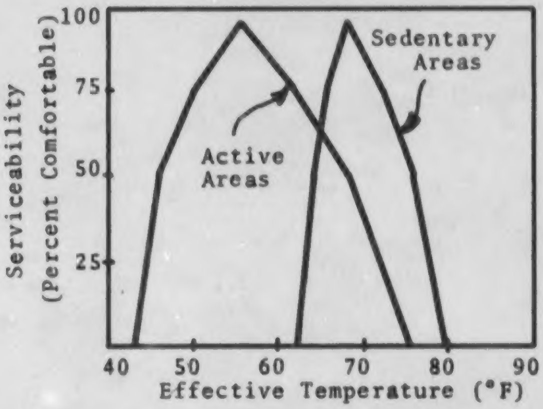

Figure 2. Serviceability with Respect to Physiological Comfort (After Pilkington Environmental Advisory Service (12))

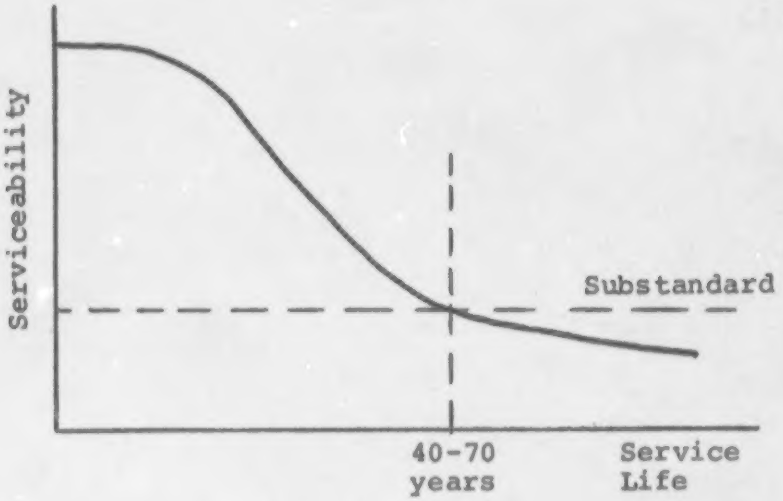

Figure 3: Serviceability trend of Urban Housing

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The Relationship of the Performance Concept to the Planning Process--Developing Performance Requirements for Community Mental Health Centers

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The performance concept is best explained as the description of a system in terms of its output rather than its parts. When this concept is applied in the procurement process of any system, the formal instrument used to effect the procurement is a performance specification.

Several advantages of performance specifications over prescriptive specifications have been suggested, particularly in the areas of economy and technological innovation.

When applied to building, performance specifications can be used at various scales of elements or systems, thus producing a "hierarchy of performance." It has been found that when used at a particular scale, the need to define the scope of the system of a performance specification requires the prescription of elements at the next higher scales.

There are several criteria for determining the scope of a system to be used on any particular project, but in general it is easier for "clear" building types than for "ambiguous" ones.

In attempting to define the scope of a system for "ambiguous buildings," one often finds oneself substituting the question "What is a house?" for the question "How should a house perform?" The former question leads to concern for earlier decisions in the planning process.

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Le concept de performance s'explique comme la description d'un système portant sur son rendement plutôt que sur ses composants. Quand ce concept est utilisé comme un élément formel du procédé d'acquisition d'un système, l'instrument utilisé pour effectuer une telle acquisition est une spécification de performance.

Les spécifications de performance ont des avantages prononcés sur les spécifications prescriptives, particulièrement dans les domaines de l'économie et de l'innovation.

Appliquées à la construction, les spécifications de performance peuvent être utilisées à différents niveaux d'éléments ou de systèmes, produisant ainsi une hiérarchie de performances. S'ils sont utilisés à un niveau particulier, les éléments du niveau supérieur doivent être prescrits, définissant ainsi l'étendue du système de spécification de performance.

Il y a nombre de critères pour déterminer la portée du système à utiliser dans un projet particulier quelconque, mais, en général, c'est plus facile pour un type "évident" de bâtiment que pour un type "ambigu".

En essayant de définir la portée d'un système pour des bâtiments ambigus, on se trouve souvent obligé de substituer la question: "Qu'est-ce que c'est qu'une maison" à la question: "Qu'attendre d'une maison". Cette question amène à s'inquiéter des décisions antérieures de plans en cours.

La Documentation pour l'aide à la planification (PAK) des Hôpitaux psychiatriques, rassemblée par le National Bureau of Standards pour l'Institut de Santé Mentale, illustre le point ci-dessus, et son développement est brièvement examiné.

Key words: Building procurement; building systems; hospital planning; office building; performance.

1. Introduction

This paper presents a discussion of the relationship between the performance concept and the planning process as a whole, when the latter is understood in its broadest sense to mean society's process of deciding on the allocation of resources and effort to effect some agreed upon end which may include environmental manipulation in general and building in particular. The paper consists of two principal parts. The first is theoretical and conceptual, and tries to demonstrate how a rigorous and pervasive implementation of the performance concept in building will inevitably lead to concern for the broader issue of the planning process. The second part is descriptive of a particular project--The Planning Aid Kit (PAK) for Community Mental Health Centers--, a project which began with the performance concept and ended with proposals to systematize the planning process itself.

2. The Performance Concept and The Planning Process

2.1 Definition and Advantages

Elsewhere in this collection of papers will undoubtedly be found several definitions of the performance concept. It is not this author's intent to offer another definition, but rather to convey its general sense. The performance concept may be explained as the description or specification of a system in terms of its performance as output, or as the service it is to provide. In this way performance is distinguished from prescription, which describes or specifies a system by a complete detailing of all its parts and the relationships between them.

When the system described in terms of its performance is a product of some kind, such as a building or a part of a building, and when this description is applied in the system's design or procurement, the formal instrument or document used is a performance specification.

Some of the advantages claimed for the use of performance specifications over prescriptive specifications in product procurement are the following:

a. encouragement of cost economies by increasing the range of possible design solutions, and thus broadening the basis of competition

b. promotion of technological innovation

c. opportunity for greater quality control

d. provision for expressing the needs of the system's users in its procurement process (since presumably the users' need for the system's output is their reason for procuring it in the first place), thereby helping assure a better fit between the system and its users' intent.

2.2 Scales of Application of the Performance Concept

Elsewhere in this series of papers, authors will undoubtedly discuss the different scales at which the performance concept may be applied in building--the "hierarchy of performance" as it has been called. It is clear both philosophically and practically that any system may be viewed as consisting of parts or subsystems, while at the same time itself being a part or subsystem of a larger system.

To use an example from building, one may consider as systems in a growing order of scale the following:

a. a fluorescent tube

b. a luminaire

c. a ceiling assembly producing illumination as one of its attributes

d. a room with specific illuminated environment as one of its attributes

e. an environment where illumination provides people the opportunity to carry out a certain activity (e.g., reading a textbook)

f. a situation within which people perceive and manipulate certain information to achieve a purpose (e.g., learning in a school situation)

Though beyond the scope of this paper, an appreciation of this hierarchy, incidently, may go a long way in clarifying the issues of the currently fashionable debate of "closed systems versus open systems." An "open" system is defined as one whose interfaces between subsystems allows the substitution of a number of different alternatives for each subsystem without changing the system's performance as a whole. In a "closed" system such substitution is not possible, and thus there is only one set of subsystems that go together to make up the system. Strong claims are made for each. But now one may consider other possibilities, such as an "open" system each of whose subsystems may be a "closed" system, a "closed" system which is itself a subsystem of a larger "open" system, an "open" system which is part of a larger "closed"system, etc. (The author is indebted to Thomas E. Ware of the National Bureau of Standards for these examples.) In light of all these alternatives, and their implied qualitative and quantitative differences, the current debate is very meagre indeed, and has in this author's opinion been glib, superficial and has led to premature and irrelevant conclusions.

2.3 Definition of Scope of System

The above discussion of the hierarchy of performance bears on another current debate--performance versus prescriptive specification.

When performance specifications are employed to specify the attributes of a system *at a particular scale*, then they must be complemented by implicit or explicit prescriptive specifications *of the next higher scale*, if the system procured by means of the performance specification is to form a viable part of a final building. Another way of expressing this idea is that the determination and definition of the scope of the system whose performance is to be specified, and the definition of the interface of that system with other elements to successfully make up a total building, are themselves prescriptive specifications. The various well known schoolhouse system performance specifications (SCSD--School Construction Systems Development, California, SSP--Schoolhouse Systems Project, Florida, SEF--Study of Educational Facilities, Toronto, RAS--Recherches en Amenagements Scolaires, Montreal) have, for example, specified adherence to a 5 foot (1.5 meter) orthogonal planning grid, a rectangular building configuration, and a 2 or 5 story limit on height--all of which are clearly prescriptive statements. Similarly, the Public Buildings Service (PBS) *Performance Specification for Office Buildings*, co-authored by the present author at the US National Bureau of Standards, specified a rectangular building plan, interior location of a rectangular building core element, a 5 foot (1.5 Meter) planning grid, a minimum and maximum number of stories, and a given percentage for net utilization of space--which are all explicit prescriptive statements.

In applying the performance concept to the process of procuring building systems, or built environments, a decision must be made at what scale to define the system whose output is to be specified. In other words, the scope of the system must be initially prescribed.

How is this scope determined, in order to maximize the benefits of performance specification as listed earlier? There are three inter-related issues affecting this decision.

The first issue is the existence or non-existence of objective means of evaluation of proposals submitted in response to such a specification--if such means do not exist at a particular scale of system, the system's scope must be reduced. As stated by Robert Blake and Michael Brill, "If performance specifications are to be a viable market instrument of procurement of building hardware, they must include three kinds of statements for each attribute specified: a requirement, a criterion and a test of evaluation means, (personal communication)." The latter must be specific solution-independent if it is to be objective in verifying compliance of different solutions with each criterion. If such a test does not exist at a certain level, clearly a performance specification cannot be employed at that level. To follow the earlier example, it may be easy to devise an objective test for the quality of illumination in a room, while it is debatable whether such a test may be devised for the quality of output of a schoolhouse or an educational situation.

The second issue is the ability of proposers to respond to a specification at a certain level--if it is anticipated that such response will be limited at a given scale of system, the system's scope must be adjusted. As the scope of the system grows in the hierarchy of performance, the nature of tradeoffs to be made in arriving at a proposal increase in scope and in range of disciplines involved. The emergence of multi-discipline organizations capable of responding to performance specifications is recent and limited. The benefit of increased competition offered by performance specification would quickly disappear if response were limited to a handful of "all-knowing" giants.

The third issue is the time and budget at the disposal of a particular project--if it is anticipated that the performance-based procurement of a system at a particular scale will exceed the available time and budget, the system's scope must be adjusted. For example, while full-scale field testing of acoustic performance of buildings is both technically feasible and well within the capabilities of a large number of potential proposers, several of the projects mentioned earlier were pressed by schedule and budget considerations to substitute laboratory testing of assemblies, representing a lower level on the scale.

2.4 Process Implications

The use of performance specification as an instrument in the building process requires some modifications of that process. Performance requires traditional process participants to undertake new roles, or to revise the schedule and order of their participation. For example, architects and designers may be required to work for product manufacturers in their preparation of proposals responding to performance specifications. Furthermore, roles for new participants are established. For example, testing laboratories play a decisive role in the evaluation of proposals.

Finally, management, schedules and legal relationships must often be manipulated, changed and redefined to accommodate use of performance specifications. For example, the signing of procurement contracts for building elements before actual buildings are finally designed, and the code compliance approval of buildings at a schematic stage in their design, are both rich in legal and managerial implications.

These process implications have been written about extensively elsewhere (e.g., Performance Specification for Office Buildings, by Hattis and Ware, NBS Report 10 527, January 1971), by those who have implemented performance-based procurement projects for building systems, and are not the subject of this paper. It is rather precisely those projects' point of departure--the determination of the scope of the system to be so procured, and the need for prescriptive specification at that point, as discussed earlier--which raises planning process implications which have not been extensively discussed or written about, and which leads to the balance of this paper.

It was an examination of two projects of performance-based procurement of building systems as to how they established the scopes of systems to be procured which spurred the author's concern with this issue.

The University Residential Building System project (URBS) aimed at ascertaining and fulfilling the needs of the users (in this case, students residing in dormitories)--such as the ability to exercise some control over the appearance and finish of the students' rooms. Yet it seemed to take for granted that the dormitory was the correct residential setting for students in the first place. The URBS performance specification could not procure any other kind of residential setting.

The PBS office building project (mentioned earlier) aimed at rigor and comprehensiveness. Yet one might legitimately ask why such rigid limitations as rectangular building plans, interior cores, etc. were imposed.

Now, both projects had not determined the scopes of their systems arbitrarily or lightly. All the issues affecting this determination (as discussed earlier) were addressed. Prescriptions were based on historic precedent (e.g., 90% plus of all recent office buildings were found to conform to the prescriptions).

Yet the questions raised have a nagging persistance. Why couldn't the performance concept offer a much wider range of options?

2.5 Clear versus Ambiguous Building Types

It would appear that building types as we know them today, and as we use names to describe them--housing, schools, office buildings, hospitals, etc.--fall into two categories, a "clear" category and an "ambiguous" one, for any particular period in time.

A building type can be thought of as tending toward the "clear" category when any or all of the following conditions are fulfilled:

a. there is general agreement on who the users of the building type are

b. there is general agreement by the users of the building type on why they need the building, on what they expect it to do for them, etc.

c. there is a cultural tradition governing the function, shape, and/or meaning of the building type

d. there is some legal requirement imposing a function, shape and/or use on the building type.

At any given time it may be possible to ascertain these, though it is clear that they are a function of history and of socio-cultural conditions. Today, one may reasonably categorize office buildings, retail shops, industrial buildings and perhaps hospitals as "clear" building types. Housing and schools are borderline cases, rapidly becoming "ambiguous," while community centers, cultural centers, mental health centers, etc. are today clearly "ambiguous." Also, one may state with reasonable certainty that all this is changing rapidly.

Yet if one undertook to introduce performance specifications into the procurement process of a building of the "clear" type, one could probably establish reasonable prescriptions for the scope of the system to be so procured, and one could justify this decision and these prescriptions. The author participated in such an effort in preparing the PBS Performance Specification for Office Buildings. At the same time, he also participated in an effort to write performance requirements for an "ambiguous" building type--Community Mental Health Centers. But here, a rigorous attempt to respond to the general question of "How should such a center perform?", or "What are the desired performance attributes of such a center?", quickly led to the earlier question "What is a Community Mental Health Center?" Suddenly, there were no answers, or rather, there were dozens of different, often conflicting answers, depending on who was being asked the question.

A brief description of the efforts to answer that question, and the result of those efforts--the development of the Planning Aid Kit (PAK) for Community Mental Health Centers--will conclude this paper.

3. Development of the National Institute of Mental Health (NIMH) Planning Aid Kit (PAK)

3.1 Background

The allocation of Federal funds for Community Mental Health Centers (CMHCs) was established by Congress in 1963. This was done within a context of evolving concepts of mental health, away from emphasis on the patient-doctor individual relationship, toward the idea that the mental health of individuals was the responsibility of their community. A corollary of that idea was that that the community was the ultimate repository of resources for providing that health to its members. Similarly, the "medical model" for treatment of mental disorder was being replaced by a process emphasizing preventive actions, treatments, rehabilitation, and custodial care.

In line with this evolution, the 1963 Act made funds available not necessarily for the construction of buildings, but rather for the establishment of an administration that would provide and coordinate the delivery of five "essential services":

a. inpatient services

b. outpatient services

c. emergency services

d. partial hospitalization

e. consultation-education programs

Buildings could be thought of as one part of such an administration. At the same time, it was proposed to exempt CMHCs from existing Federal building standards, and especially those for hospitals, for the purpose of de-institutionalizing the services and promoting innovative programs.

Finally, application for CMHC funding had to be generated locally, with "maximum feasible participation" of the community.

The Architectural Consultation Section of the National Institute of Mental Health (NIMH) was created to carry out four basic functions:

a. consult to communities on proposal preparation

b. participate in proposal evaluation

c. coordinate solutions of implementation problems

d. apply feedback to other communities in other areas

This emphasis on user needs, combined with new concepts and an innovative objective, appeared to offer a unique opportunity for applying the performance concept. With this opportunity in mind, the Architectural Consultation Section contracted with the National Bureau of Standards to develop performance standards to enable it to carry out its functions more efficiently, rigorously, effectively, and replicably.

In recognition of the great variety of users of mental health facilities and the basic need of performance standards to reflect this variety, the initial approach taken was to devise a set of typical user characteristics (e.g., age, sex, socio-economic, ethnic, etc.). This set formed one dimension of a three-dimensional matrix that would ultimately include all the performance statements of CMHCs for all possible users. (The other two dimensions of the matrix were to be building elements and attributes.) Thus, if one could describe a group of users of a potential CMHC, the matrix would permit a simple retrieval of performance attributes for the group's characteristics, and these could be the basis for performance specifications for such a CMHC.

In attempting to visualize how such a system would work, it was realized that this approach, based on a generic users characteristics axis, would be too general to display all the richness and variety which an intuitive reflection on CMHCs suggested. It seemed that similar users would generate different requirements depending on the mental health problems with which they were faced. Furthermore, a given group of users, faced with a given problem, would still be faced with alternative courses of action, each of which could itself generate different environmental requirements.

The desire to maintain and promote this richness gradually led to the realization that not a static storage and retrieval system of all possible performance attributes, as represented by a 3-dimensional matrix, was needed, but rather a planning process that could raise and display relevant issues, elicit decision making, and ultimately lead to the generation of a particular solution in terms of environmental performance attributes, was what this project called for.

Such a planning process had to be usable by a variety of participants, ranging from mental health professionals to community representatives. The first step, that of selecting the planning process participants, was viewed as a political issue and left to the political process.

The resulting planning process as proposed was viewed as having several necessary characteristics:

a. it would be an educational process for all its participants

b. it would help to define "community," and elicit its participation

c. it would provide instruments for decision making

d. it would record and document all of its phases for ease of future review, revision, and evaluation

e. it would be replicable for a variety of conditions, repeatable in format

f. it could be used for applications for funding

g. it could be used for constant updating of facilities and programs

3.2 The Planning Aid Kit (PAK)

The process proposed to NIMH to fulfill these requirements was the Planning Aid Kit (PAK) which consisted of a series of forms to be used at a series of meetings of participants, both for purposes of exchanging information and making decisions.

PAK was devised to get the appropriate information to the designers of the environment and to the administrators who must evaluate the suitability of their designs. It is essentially a device for people to articulate their problems so that planning the environment may respond to them. To do so, it subjects information to a series of transformations in several steps:

a. problems

b. courses of action

c. activities

d. environmental characteristics.

The latter, in turn, are used to find, modify, or build settings of a CMHC.

Each step of the series of transformations has a form designed to elicit and display information, and the actual translation from one step to another is accomplished by forms designed to foster decision making.

It is beyond the scope of this paper to describe PAK in detail. Four basic points should suffice:

1) The problem forms relate stated problems to particular groups of the community. They develop information about these problems in terms of recording perceived causes and effects of stated problems, each of which, in turn, may become a problem for further discussion.

2) The courses of action are mobilizations of resources to solve problems, of which many alternatives may exist for each problem. The relation of courses of action to specific problems is a major departure from the current categorization of mental health programs, which is either by service provided or population served (e.g., "programs for the elderly," "emergency," "outpatient," etc.).

3) The activity forms are designed to display alternative sets of activities for each course of action, at a scale sufficiently fine to impose some environmental requirement (e.g., "playing with blocks," "participating in group discussions," etc.).

4) The environmental characteristics are basically a set of semantic differentials designed to quantify environmental requirements (e.g., "privacy-communality," "familiarity-remoteness" etc.) in a way that may be correlatable with physical aspects of the environment.

The filled-in forms produced by the PAK process have value beyond helping the participants educate themselves and make decisions. They represent a statement of what the proposed programs are to accomplish, and can thus form part of the application for funds, as well as become part of a central data bank to be used by other groups in their own planning, as well as source material for developing further programs.

4. Conclusion

Since the development of PAK, it has been applied experimentally in several CMHC programming situations. Clearly, such experimental application should lead to revision and improvement. NIMH has recently awarded a substantial grant for a systematic application and further development of PAK.

While the above discussion of PAK is clearly insufficient to do it substantive justice, it does demonstrate the central thesis of this paper, that applying the performance concept to certain building types may often lead far afield--to concern for the planning process itself, and to revision of that process.

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Institutional Performance and Building Performance: Some Implications of the Judicial Facilities Study

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The performance of the institution or organizations which buildings serve has not been regarded as within the province of architectural analysis. Failure to evaluate institutional requirements can result in buildings which hamper rather than help the performance of institutions. A critical examination of the objectives and operations of the judicial system was a major theme of the Judicial Facilities Study, designed to develop standards and guidelines for courthouse design in the United States. How these facility standards were derived from a detailed examination of the judicial system is explained in terms of: the ways in which judicial system requirements and personal human requirements were handled; the present and future purposes and human needs the system and its facilities seek to fulfil; the manner in which the operations of each court function and specialized proceeding were examined; the ways in which activities, interpersonal relations, communication patterns, environmental and spatial characteristics were analyzed. Certain conceptual and theoretical considerations implicit in the approach to the study are discussed. The assumptions of conventional architectural analysis are stated, and the physical determinism inherent in them criticized. An alternative hypothesis is advanced, namely, that the effect of the physical environment on human performance varies with institutional performance. Buildings and the operations of the institutions they house are seen as interdependent, mutually adapting to each other as the people involved attempt to achieve correspondence between the two. The ideal of perfect consonance is viewed as able to be approached only if the designer has a thorough understanding of the institution both as it is and as it ought to be.

La notion de performance appliquée aux institutions ou aux organisations servies par les bâtiments n'a pas été considérée comme ressortissant du domaine de l'analyse architecturale. Le manque d'évaluation des exigences institutionnelles peut aboutir à des bâtiments qui gênent la performance des institutions plutôt qu'ils ne la facilitent. Un examen critique des objectifs et des opérations du système judiciaire a été un thème principal de l'Etude des Installations Judiciaires conçue afin de développer des normes et des directives pour la planification des tribunaux aux Etats-Unis. Comment ces normes d'installations ont découlé d'un examen détaillé du système judiciaire, ceci est expliqué en fonction de: la façon dont les demandes du système judiciaire et les exigences humaines ont été traitées; les buts présents et futurs et les besoins humains que le système et ses installations cherchent à accomplir; la manière dont les opérations de chaque tribunal, quant à sa fonction et ses activités particulières, ont été examinées; la façon dont les activités, les relations interpersonnelles, les modes de communications, les caractéristiques d'environnement et d'espace ont été analysées. Certaines considérations conceptuelles et théoriques implicites à la direction de cette étude sont discutées. Les idées directrices de l'analyse d'architecture traditionnelle sont exprimées et leur déterminisme physique inhérent est critiqué. On propose une alternative: l'effet de l'environnement physique sur la performance humaine varie avec la performance institutionnelle. Les bâtiments et les opérations des institutions qu'ils abritent sont considérés comme interdépendants, s'adaptant réciproquement cependant que les personnes en cause essaient d'établir une correspondance entre les deux. On considère que l'idéal d'un accord parfait ne peut être accessible que si l'architecte a une connaissance approfondie de l'institution aussi bien en ce qu'elle est qu'en ce qu'elle devrait être.

Key words: Activities; communication; courthouse; human performance; institutional performance; judicial system; mutual adaptation; objectives; operations; physical determinism; physical environment.

1. The Place of Institutional Performance in Architectural Analysis

In conventional architectural analysis the institutions or organizations which buildings serve are not subjected to critical examination. The starting point is people and their activities as the analyst sees them in operation or as he is told about them by active participants. The activities are accepted as given and not questioned as to their necessity or desirability. From these are derived spatial requirements and space arrangements. Fundamental concerns of the conventional type of analysis are whether acceptable standards of human health, comfort and efficiency are met, and circulation and communication facilitated. Whether the institution or organization is doing its job properly is not questioned.

Once this questioning takes place, it opens the way for the addition of a whole new dimension to architectural analysis, namely an evaluation of the performance of the institution or organization itself. Such evaluation requires a thorough understanding of the operations of the organization, its role in society, and the degree to which it is performing in accordance with that role. Detailed attention to institutional performance could lead to a reevaluation of operations and could have a profound effect on personnel, activity, circulation and space requirements. The result is likely to be a building designed to meet not the requirements of the institution as it presently operates but as it should or is likely to be operating in the future.

It might be objected that this type of institutional analysis is beyond the scope and competence of those whose job it is to determine building requirements. It is indeed true that architectural analysts do not now have such competence. Yet consider the consequence of accepting the existing practices and operations of the institution or organization. Because the most vital institutions are precisely the ones which today are undergoing very rapid changes, a building which fails to take such changes into account becomes obsolete very quickly so that the ratio of costs to benefits received is unduly high. Clearly, if the building is to meet the need of the institution not only now, but during the next decade or two, the requirements of the institution during the foreseeable future must be investigated. It is not sufficient to rely on the haphazard viewpoints about the future by those who use existing buildings. Something more definitive is necessary, grounded in a thorough study of the emerging developments and needs of the institution. Uncertainties about the future would still make it desirable to build flexibility into the building. But the architect would then have at his disposal the necessary knowledge to enable him to program the range of flexibility in advance and see to it that the right kind is built into the structure.

The consequence of failure to understand institutional requirements is well illustrated by what has happened to public housing projects in several large American cities. For decades the emphasis was exclusively on providing healthful and sanitary abodes. In too many instances these have deteriorated physically and have themselves become slum ghettos of racial and low-income segregation. Neglected until quite recently were the social needs of the inhabitants and the requirements of the family as a social institution as distinct from the household as a physical entity. The remedy involves a consideration of the family in terms of its internal social structure, its relation to other families and its role in the larger community. Actually the buildings hampered rather than helped the performance of the family as a social institution.

2. The Judicial Facilities Study

The Judicial Facilities Study attempted to relate building requirements to performance criteria for the system of judicial administration. The study was instituted in 1968 under the joint sponsorship of the American Institute of Architects and the American Bar Association. It took two and a half years to complete by an interdisciplinary team of lawyers and architects under my direction. Its purpose was to develop standards and guidelines for courthouse design in the United States. Coverage was comprehensive, encompassing acoustical, thermal and lighting requirements, unit space sizes, space relations, arrangement of spaces and spatial attributes for general trial courts and all their component spaces as well as for the various specialized courts existing in the United States, e.g., appellate, juvenile, traffic. The study was directed towards obtaining courthouses which would promote not only the health, well-being and efficiency of those using them but also the effectiveness of the judicial system as a human institution. Its twofold analysis of system requirements and personal human requirements proceeded along the following lines:

2.1 Judicial System Requirements

First, the objectives of the system were analyzed in detail for the system as a whole and for each of its many components. They were explicit and formulated in a manner which would make them operationally useful. Objectives were clearly distinguished from functions or operations as being the fundamental reasons why the functions or operations are performed. The role of objectives in the analysis was to provide a basis for evaluating the practices of the institution and the effectiveness of its facilities. A knowledge of the purposes and human needs the system and its facilities seek to fulfil permits performance to be measured against purpose so that a correspondence between them may be achieved.

The whole purpose of law and its administration was shown as revolving around some notion of justice, around a normative standard for the arrangements of men's lives together. As such, the objectives of the courts take on a threefold character: they are directed toward the individual human beings whom the court serves; they are concerned with the functioning of the judicial system itself so that it may adequately do the job for which it exists; and they are entwined with the needs of society, of which the system of justice is perhaps its most enduring symbolic form.

A synoptic ordering of the myriad of objectives set forth in the individual chapters of the study reveals three themes looming large on the comtemporary scene. (1) The confidence of the public in the judicial system is a major concern of our time. If the system is to function effectively, there must be a high degree of public acceptability and reliance on the authority of the courts. (2) A second major theme has to do with the way the courts operate. At issue is their efficiency and competence. If the demand for prompt and speedy justice is to be achieved, the best available technology and management practices are indispensable. Without these, justice becomes either increasingly difficult to obtain or is obtainable at unnecessarily high monetary costs. (3) A third major theme has to do with the various kinds of help the judicial system can and should give to those in need of assistance, e.g., adequate legal assistance for those who cannot afford it; the obligation to help those guilty of criminal acts obtain effective treatment for their anti-social propensities so that they may be rehabilitated for their own sakes and for the protection of society; special care and solicitude for children involved in any way with the courts. Concern for human needs should be one of the distinguishing marks of a modern judicial system.

Next the operations of each court function and each specialized proceeding were analyzed. This analysis was based on intensive field studies of different size courts in various parts of the country. Dealt with were such matters as the way in which a case moves through a court, the flow of paperwork through a clerk's office, the step-by-step proceedings in a trial. These operations vary with the type of case or court function. Thus in a criminal proceeding, a different set of operations is performed than in bankruptcy or appellate proceedings. Each of these was described in detail and summarized in diagrammatic form. Every attempt was made to incorporate the best current practices and those which foreshadow future developments. One example is the use of computers to help improve efficiency and avoid the delays which hamper the functioning of the courts. Another is the movement towards an all-inclusive family relations court. Still another is the shifting from judicial to administrative or arbitration procedures, e.g., some automobile insurance cases and small claims.

Operations and objectives are connected in a means-end relationship. Whether the judicial system is operating in a satisfactory manner depends upon whether it is achieving its objectives. The evaluation of its modes of operation, therefore, requires an understanding of objectives.

2.2 Personal Human Requirements

Next, the activities which must be carried on in connection with each particular function or procedure were identified, together with the kinds of people involved and the kinds of spaces required. It can readily be seen that the analysis of operations is a necessary intermediate step between objectives and activities, for any modifications of operations to meet objectives will be reflected in modifications of activities.

The next step in the analysis revolved around the interpersonal relations of participants in the light of the activities in which they are engaged. Desirable relations of this sort are determined by the objectives, should be fostered by operations and can be facilitated by appropriate communication patterns. For example, the rehabilitation of convicted felons can be fostered by judicial proceedings geared to helping rather than antagonizing the accused and to promoting certain kinds of interpersonal relations between him and the other participants in his case as it moves through the courts. Such relations can be facilitated by space arrangements which promote ease of communication of the right kind. Such considerations led to a study of desirable communication patterns.

The analysis of communication was mainly in terms of movement between activities. During a trial, however, communication occurs with relatively little movement, once the participants are in their places in the courtroom. Consequently, for the trial function four variables were analyzed: visual communication, audio communication, passing of documents and movement of people. What was sought here was the disposition of people and activities within a space, where these four variables are the chief conditioning factors. Elsewhere what was sought was the disposition of spaces in relation to one another. If each space is associated with a set of activities, the chief conditioning factor is the movement occurring between the sets. A stronger relationship exists between activities where large numbers of people move from one to the other for significant reasons, than between activities where people seldom find it necessary to meet each other. The spaces containing the former activities should then be more easily accessible to one another.

Data on movement and communication were obtained through the field studies mentioned earlier. Particular attention was paid to volume (or frequency) and to significance for the particular function under consideration. This permitted a quantification of the data in terms of the relative importance of the movement or communication between the different activities. The values assigned were organized in matrix form, an example of which is shown in figure 1. As between two activities, more movement may start from the first and be directed towards the second than is the case for the reverse movement. The matrix shows the movement from each activity to every other one, so that the movement from, say, preparing jury lists to selecting jurors is given separately from the reverse movement from selecting jurors to preparing jury lists. The relative values assigned to each of the movements are based on a 0-3 scale. For each function, two matrices were constructed, one for volume and one for significance of movement, with the largest numbers denoting the greatest volume and significance. The figure in each box of the volume matrix was multiplied by the corresponding figure in the significance matrix to arrive at a measure of relative importance on a 0-9 scale. Each horizontal row then shows the relative importance of movement from one activity to each of the others; and each vertical column shows the relative importance of movement to one activity from each of the others. When the figure of movement from one activity to another is added to the figure of reverse movement between them, a measure of total movement between them is obtained. When the figures of a row are summed, a measure of total movement from a given activity is obtained. Similarly, the sum of the figures in a column gives a measure of the total movement to a given activity. Composite matrices of volume and significance denoting relative importance of movement or communication were developed for each of thirty court functions and specialized procedures.

The conclusions regarding the relative importance of movement were then shown in simultaneous form in diagrams depicting the total pattern of movement for each function or specialized procedure. An example is given in figure 2. The closer two activities are to each other and the thicker the line connecting them, the more important is the movement between them. Also, the greater the number of lines which converge towards any particular activity and the thicker they are, the more important is that activity as a node or focus of movement. Each diagram is a visualization of how every activity should simultaneously be related to every other activity in order to facilitate movement or other type of communication among them. From the network of lines groupings emerge which tell at a glance how activities should relate to one another. Thus figure 2 shows a close grouping of five General Trial Court functions: trial, chambers, hearings, clerical and legal, each of which is a major node of movement. The remaining functions are of lesser importance in the movement system.

These movement patterns were then translated into other diagrams where activities are replaced by the spaces associated with them and where the structure of the corresponding movement pattern is preserved. An example is given in figure 3. These interspatial movement patterns are designed to show how all required spaces should be related to each other in order best to facilitate the movement that has to occur from one to another.

The analysis was completed by studies of atmospheric, light and sound conditions and other characteristics of the required spaces. Each of these was studied in the light of the activities, operations and objectives associated with the particular space under consideration. Together with the spatial arrangements, they provide guidelines for the planning of the total physical environment.

3. Conceptual and Theoretical Considerations

Characteristically, architectural analysis is directed towards coming up with space requirements which would satisfy an efficiency criterion, namely maximization of the effectiveness with which people function and tasks are performed. The basic assumption is that personal human performance is in a relation of functional dependency to the arrangement and attributes of the space people occupy. Three further assumptions are implied: that performance varies inversely with the amount of physical effort expended upon tasks or activities; that physical effort varies inversely with ease of communication; and that ease of communication varies inversely with the time it takes to communicate and the distance between those communicating. Hence the spatial arrangement of people and activities should be such as to minimize their distance and communication time. Hence also, the acoustical, thermal, lighting and other attributes of spaces should minimize auditory, physical and optical effort.

The physical determinism inherent in these assumptions is open to serious objections. Decades of empirical investigation and controlled experiments have failed to produce unambiguous results as to the effects of the physical environment on human performance. The degree of influence of thermal, lighting and acoustical conditions on human physiological, perceptual and task performance is far from clear. The most definite correlations have been observed in the short run and especially in short run stressful situations, neither of which is particularly useful for buildings. If one were to attempt a general conclusion it might be that changes in the physical environment have a great influence on human performance under extreme physical conditions, their effect diminishing rapidly thereafter and having little or no impact under "normal" conditions. In fact, under favorable operational conditions, substantial degradation of the physical environment has failed to halt expanding task performance. Also, in the case of public housing unfavorable social conditions have led to a degradation of the physical environment itself.

These considerations suggest an alternative hypothesis to the one of physical determinism, namely that the effect of the physical environment on human performance varies with institutional performance. An environment which minimized physical and work effort, or facilitates ease of communication, will not of itself enhance human performance. The extent to which it does so depends on the way in which the institution is doing its job. It is this which motivates or fails to motivate its participants, and without it no amount of improvement in their physical environment will enhance their efficiency or their effectiveness as human beings. It is not necessary that the needs for which the institution exists be completely met, for no institution is perfect. What must be present is a belief in and approval of the direction it is taking. Then the proper physical conditions will make it easier for participants in its processes to do what they already want to do or behave in a manner favorable to its working. This in turn will enhance the capability of the institution to achieve its objectives. The initiating force must come from the way in which the institution is performing. Only when the institutional conditions are favorable will the impact of the physical environment be felt, not only directly on personal human performance but as feedback on the performance of the institution as well. The reverse occurs when the workings of the institution generate indifference, opposition or alienation. Then changes in the physical environment tend to be stillborn and barren of results.

Complementing the above hypothesis is another way of looking at the relation between buildings on the one hand, and personal and institutional performance on the other. This may best be couched in the somewhat ecological language of mutual adaptability. The way in which things are done affects activities and the organization of space. Conversely, the way in which space is organized affects the way in which things are done and the activities carried on in that space. What it is possible to do depends to some extent on the facilities available. Thus, the absence of laboratory facilities in a school will condition the way science is taught and affect the performance of the organization in terms of some objective standard of educational achievement. Furthermore, if the physical environment does not conform to the operational requirements of the institution, the users will tend to modify it as best they can in order to facilitate operations. As has often been observed, building spaces are not always utilized as the architect intended them to be. Families constantly change the space arrangements in their houses to meet the changing demands of family living, privacy and sociability. The physical environment and the operations of the institution act and react upon each other in a system of mutual interdependency.

There are obvious limits to this process of mutual adaptation. A building may be too obsolete, small or spatially rigid to be changed satisfactorily in response to institutional changes. It may become a straight-jacket forcing the institution into undesirable ways of doing things and impeding its workings. Then, institutional requirements are not satisfied, felt human needs neglected, objectives not met and operations deteriorate. Because adaptation is no longer possible, the system undergoes distortion. When the building cannot be adapted to the institution, the institution will be adapted to the building. Only in this way can the necessary correspondence between the two be achieved. Such efforts to achieve correspondence usually leads to inadequacies in both institutional and building performance.

Perfect consonance is indeed rare and generally short-lived. Only in a few great ages of architecture do we feel it to have been achieved. Apparently, for example, the planner-builder-designers of Gothic cathedral after Gothic cathedral were so steeped in the religion of the time that they had a real insight for what was required to the point of possessing an almost intuitive feeling for the right and somewhat lasting solution. This is seldom possible for the designer of modern buildings. In the case of judicial facilities, the designer must live "the life of the law." Since this is not part of his way of life, he can only substitute for its absence (1) an intellectual and analytical knowledge of the administration of justice and its objectives, (2) a close collaboration with those who live that life in the real sense of the term. The Judicial Facilities Study attempted to provide the first, while giving summary guidelines how best to achieve the second. If institutional performance is to become an abiding concern of architectural analysis, a somewhat similar procedure is implied for other human institutions.

MOVEMENT TO MOVEMENT FROM	PREPARING JURY LISTS	NOTIFYING JURORS	INTERVIEWING JURORS	SELECTING JURORS	ASSEMBLY OF JURORS	IMPANELING OF JURORS	TRIAL PARTICIPATION	JURY DELIBERATION	JURY SEQUESTERING	TOTAL MOVEMENT FROM
PREPARING JURY LISTS		9	6	9	0	0	0	0	0	24
NOTIFYING JURORS	9		6	9	6	0	0	0	0	30
INTERVIEWING JURORS	6	6		9	0	0	0	0	0	21
SELECTING JURORS	6	9	9		0	0	0	0	0	24
ASSEMBLY OF JURORS	0	9	0	0		9	6	0	0	24
IMPANELING OF JURORS	0	0	0	0	6		9	0	0	15
TRIAL PARTICIPATION	0	0	0	0	0	9		9	0	18
JURY DELIBERATION	0	0	0	0	0	0	9		3	12
JURY SEQUESTERING	0	0	0	0	0	0	0	3		3
TOTAL MOVEMENT TO	21	33	21	27	12	18	24	12	3	

FIG. 1 JURY : MOVEMENT OF PEOPLE BETWEEN ACTIVITIES

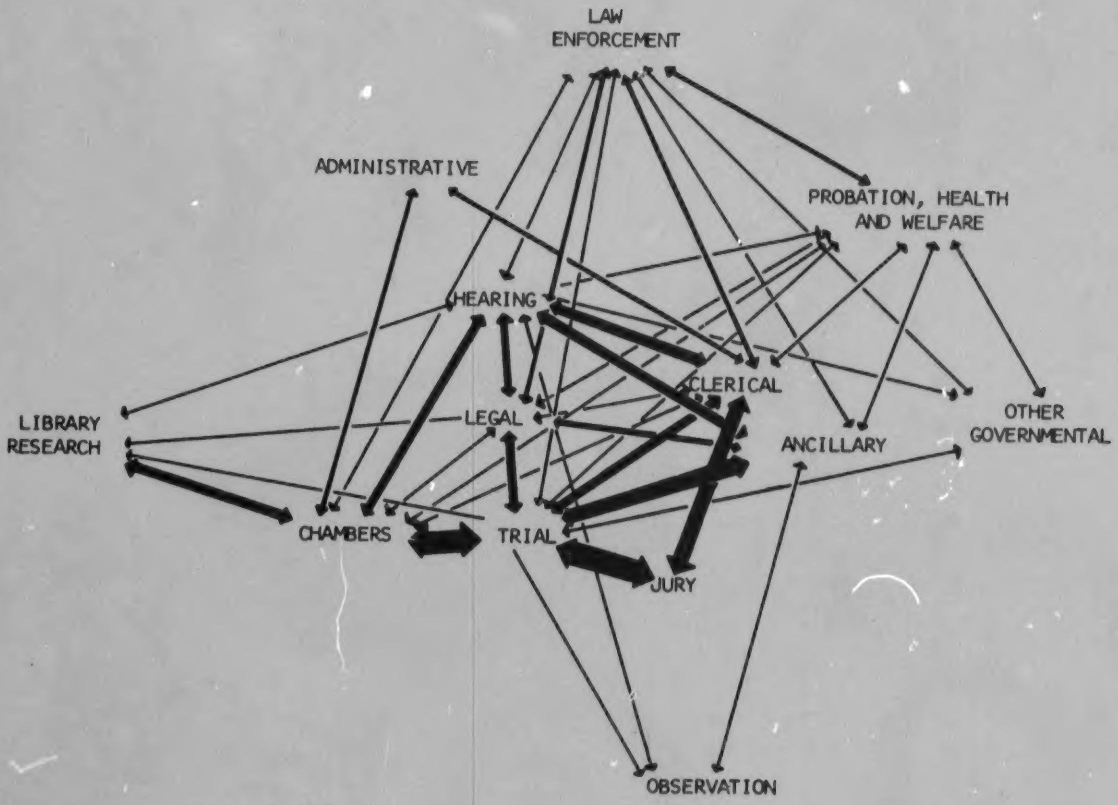
LAW ENFORCEMENT
ADMINISTRATIVE
PROBATION, HEALTH AND WELFARE
HEARING
CLERICAL
LIBRARY RESEARCH
LEGAL
ANCILLARY
OTHER GOVERNMENTAL
CHAMBERS
TRIAL
JURY
OBSERVATION

FIG. 2 GENERAL TRIAL COURT : MOVEMENT SYSTEM

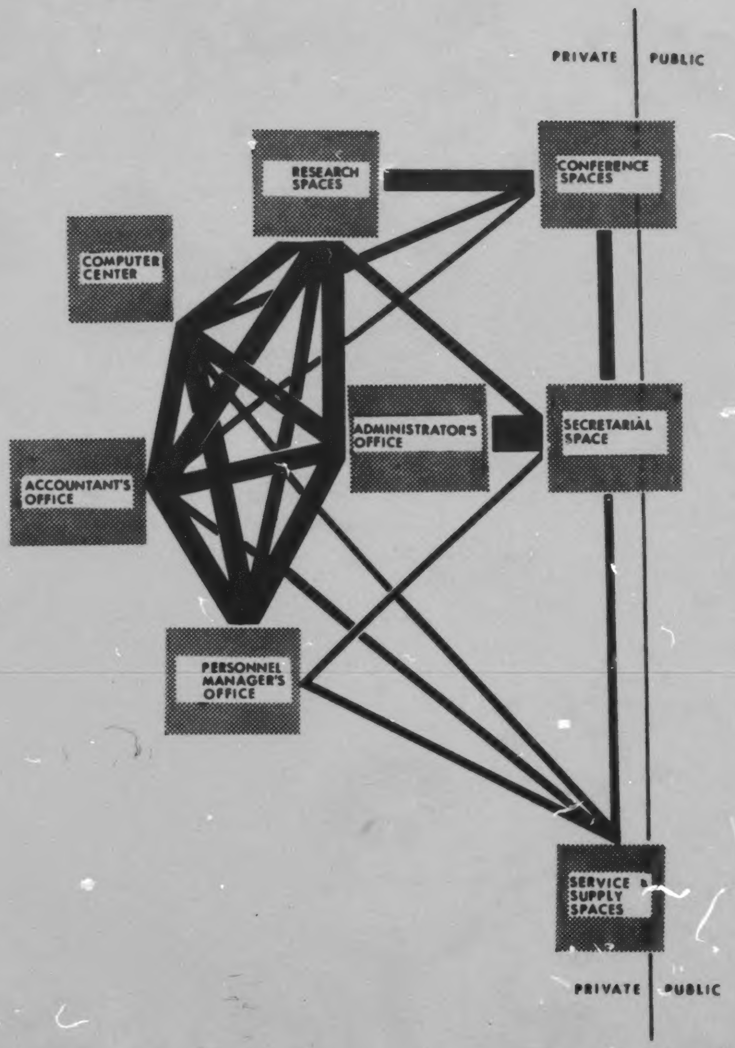
PRIVATE
PUBLIC
RESEARCH SPACES
CONFERENCE SPACES
COMPUTER CENTER
ADMINISTRATOR'S OFFICE
SECRETARIAL SPACE
ACCOUNTANT'S OFFICE
PERSONNEL MANAGER'S OFFICE
SERVICE & SUPPLY SPACES
PRIVATE
PUBLIC

FIG. 3 ADMINISTRATIVE : INTERSPATIAL MOVEMENT PATTERN

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The Complementary Use of Research and Negotiations with Users in the Development of Performance Standards

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Two assumptions underlying much of the current discussion about industrialized building systems for housing are: (1) research should investigate the needs of users of housing, and (2) the resulting findings can be cast into explicit performance standards or specifications to permit industry to develop and mass produce housing systems conforming to these standards and to the needs of users.

These assumptions are questioned. If user requirements research is to produce useful results, it must focus upon users in actual decision-making situations and be complemented with procedures of negotiation, conflict-detection, argumentation, debate, bargaining and conflict-settling.

An approach is discussed which puts research into the implementation phase of actual projects as a part of the planning discourse and decision-making process.

A la base de beaucoup des discussions courantes au sujet de systèmes de construction industriels dans le logement, on trouve l'idée que les études entreprises devraient examiner les besoins des usagers et que les renseignements obtenus pourraient être classés en normes ou spécifications explicites de performance pour permettre à l'industrie le développement et la production de masse de systèmes d'habitation se conformant à ces normes.

Cette conception est mise en doute. Si l'étude des demandes des usagers doit produire des résultats utiles, elle doit se concentrer sur les usagers dans de vraies situations de prise de décision et doit être complémentée par des méthodes de négociation, de déviation de conflits, d'argumentation, d'achat et de résolution de conflits.

Une approche est examinée qui étend les recherches jusqu'à la phase d'exécution des projets réels, comme une partie de l'étude de planification et du processus de prise de décision.

Key words: Arguments; decision-making; IBIS (Issue Based Information System); negotiations; research, structured planning discourse; user needs, -aspirations, -values.

1. Introduction

The development of industrialized building systems for the housing sector is entering into a new phase of large-scale corporate effort, aiming at large aggregated markets and integrated systems embracing structure, enclosure, interior finishings, installations, utilities, and including the public services of new communities. At the same time, government activities are increasing in this area, in part called for by industry to help carry the development burdens and to guarantee the necessary market size, but also trying to govern and control the development on its own terms, providing the framework for industry activity, striving to secure quality and safety standards and attempting to control the social implications of the housing problem which industry is, understandably, inclined to ignore.

This development means that at many levels people are making unprecedentedly far-reaching decisions which cannot be based on traditional criteria. As a result, industry and government are calling for better guidelines, criteria and decision rules. Discussion has concentrated increasingly on the "performance concept" or performance specifications. These can be interpreted as a set of statements which, (while not prescribing specific materials, products or technologies) permit a decision-maker to deduce in each specific case whether a product or system is acceptable or not, or to judge which of a set of proposed alternatives is most desirable.

It is expected that performance standards can be based on research concerning the needs of the prospective users of a system in question.

2. Expectations

It is necessary to take a closer look at this call for research. In a rather simplified way, the expectations could be described as follows:

- Scientific investigations should be conducted to find out what different groups of users (housing, for example) need with respect to the properties of their built environment.

- The outcome of such research should be stated in terms of unequivocal user **needs** requirements. Preferably, this should take the form of lists of variables which can be easily verified in specific cases, so that decisions are not likely to be questioned afterwards because of conceptual vagueness or uncertainty about the actual qualifications of a given solution.

- The standards of performance should be set, according to the research findings, as values or ranges of values of the variables.

- With these prerequisites, industry could develop building systems to meet the prescribed performance standards - and/or present their systems for testing and evaluation (but against criteria known beforehand). This would leave industry free to develop efficient technical solutions to well-specified problems--and the government would verify (measure) the ability of a given product to meet the standard.

3. Questions

Are the preceding expectations and assumptions realistic?

It is our contention that they are unrealistic and that they represent a step in the wrong direction. There are a number of reasons for this: the first, and probably most important, rests in the concept of user needs. While it appears quite reasonable to base developments of building systems upon user needs the attempt to state these needs generates either narrow, abstract statements concerning trivial physiological conditions, which are not sufficient to distinguish and select among alternative design solutions. Or, in the process of more discriminating specification, a number of disturbing properties are found:

1. "user needs" change over time, i.e. these requirements are not sufficiently stable even within the same individual to permit an unequivocal statement that such and such must be the case. Some such changes (such as aging) are involuntary and predictable subject to fads and fashion.

2. people are different: while many groups can be distinguished with identifiable differences in their "needs," the transitions from one group to the other are blurred.

3. "user needs" are dependent on the social context: a person may exhibit quite different "needs" in one society than when he is moved to another; another way of saying the same thing is that they are dependent on tradition and quite arbitrary conventions. For example, we are used to buildings providing shelter from weather conditions, space, light, water, etc. but generally not furniture, stereo sets or food. And the possibility that a home might be also a means of transportation is still treated as a special case as far as codes, zoning regulations, etc. are concerned.

4. "user needs" are technology-dependent. We cannot realistically separate the requirements for building systems from the technological means envisaged to be part of the system. For example, lighting requirements or the simplest sanitary standards of today would have been considered unreasonable demands in the context of 16th century technology. This is expecially critical when we are dealing with innovations: performance standards for sailboats or horse carriages of the kind aimed at in construction now would never have permitted introduction of the steamship nor the automobile; these examples reveal that we should talk about user "ambitions" and "aspirations" rather than "needs";

5. whereas initially one might have started from notions of a contradiction-free, somehow "natural" system of user needs, talking about aspirations makes it quite evident that these may be conflicting, counteracting or mutually exclusive. This means that in a planning case, decisions have to be taken to "resolve" these conflicts, i.e. to strike a balance between them, or decide against one aspiration-need in favor of another.

6. It should be equally obvious that such decisions can only be taken on the basis of personal values. But, if this is true, the notion of valid performance standards based on what we now would understand by "user needs" cannot be maintained: the setting of a balance--or a decision favoring one of two conflicting objectives is a completely arbitrary act. This kind of information can only be obtained from the individual user in a specific concrete situation, and the researcher has no scientific, moral, ethical or political mandate to make these decisions in lieu of the user or those affected by such decisions. Taking averages of "prevailing" opinions, extending trends of past attitudes, etc. are obviously not viable alternatives either.

A remark is in order at this point about such "needs" as that of the user's desire to make decisions about his environment himself. If it were admitted that this might be a genuine concern, then there is no justification for assembling an elaborate system of performance standards. This cannot be helped by providing fake "choices" among pre-established alternatives. It should be clear that what is meant is the generation of such alternatives by the user himself. Without falling into extensive philosophical discussions, a strong case can be made for the contention that it is precisely this feature by which man develops and maintains his identity, dignity, self-image. However, one might object: the means of self-expression have been abandoned, succeeded by others and left to standardization--why should we insist that housing be a means of self-expression? But these are questions that cannot be decided upon by research, industry, nor government--they must be discussed.

This discussion of user aspirations and values shows an emerging dilemma. With respect to technological innovations, the prospective user cannot develop a proper value position in a void, remote from the experience of or responsibility for the consequences of a decision. This might well be the reason for so many failures of the "ask the user" approach, which has led to the prevailing attitude that the user does not know what's best for him." It must be maintained that he cannot know if he is merely confronted with abstract alternatives. He cannot judge if he has no share in the development of solutions and responsibility in the decision. But at the same time, nobody else can legitimately pass value judgments about alternatives and their consequences in the prospective user's behalf. The problem, of course, is even more complex in the many cases where the users are not known.

The second major objection to the idea of a system of performance variables--even if we assume that we are considering questions which are not personal judgments. The legitimate but disastrous quest for hard "objective" criteria carries with it the temptation to concentrate upon variables which can be readily measured and to neglect those which do not lend themselves to easy quantification and verification. But perhaps more critical is the extension of this temptation to research itself. Researchers today are under very much the same pressure as other workers to produce useful results in short time--and since the field of investigation is at any time more complex and greater than can be handled, it is only normal to focus upon the easier tasks first. Moreover, scientists distrust dealing with variables and concepts that are not fully defined, quantified, etc. No matter how important work on such aspects might be, researchers shun tasks for which they might possibly be labeled as "unscientific."

These observations nourish the suspicion that the models which serve as the working base for research investigations might, on the whole, be equally slanted toward preoccupation with easily quantifiable entities. It should be obvious that models in which important variables are omitted because one does not know how to measure them are of rather limited usefulness. It should be pointed out that this by no means should be understood as a criticism of models which have been proposed, nor as an accusation of arbitrary, even cynical omission of variables from models in which they should appear, but rather as a suspicion that (though unwittingly) the difficulties outlined above influence the very choice of models for investigation. Here we have another source of error which has been given little attention,--and which is of little concern in a single research task, but which becomes extremely critical when seen from the point of view of the effort to develop an overall, coherent complete set of performance measures and standards for a field such as housing.

Third, even if we assume that somehow a set of performance variables has been derived and that they, indeed, can be measured, in very few cases will we find that there is precisely and only one value of that variable which must be achieved. An acceptable range of values will probably be the normal case, or also all values below or above a certain point will be acceptable. This does not present a great obstacle to the evaluation of alternatives, since of two different values one can always be judged as "better" or "more desirable" than the other. (The only difficulty might be in saying "how much better" which is, once more, a problem of value and judgment.) But if we are talking about standards: where should the standards be set? It is a commonplace observation that standards which are located close to the minimum acceptable values tend to produce solutions which are just that: barely acceptable. But deviating from that minimum usually costs money--how much do we want to pay for that quality standard? These are, again, questions which cannot be resolved by research.

The preceding considerations have shown that the role of research must be viewed with some caution, and that it is least useful in that area which industry and administration would like most: the alleviation of the burden of responsibility for their decisions. Furthermore, some of the difficulties make performance standards appear as less of a solution to our troubles than much of the recent discussion would indicate.

This does not mean, of course, that research efforts should be abandoned or that efforts to develop performance measures should be diminished. But their respective uses and roles within developments such as that of industrialized solutions to the housing problem must be redefined.

4. What is Needed?

The following suggestions may serve as a first step toward an outline of what we need:

4.1 Performance measures

Performance measures and statements as the objective of research efforts, in our opinion, should not be considered as an ultimately "complete" set of standards to which all decisions could be referred, but rather as a frame of reference for the discussion which undoubtedly will go on for a long time. The rationalization for decisions to develop or support the development of particular systems, and finally to implement such systems, must be sought elsewhere.

4.2 Research

If the above contention is correct (i.e., that some of the critical information needed consists of user's value attitudes and judgment, and that users can develop such judgment only when confronted with the real choices and responsibility for the decision). then research must focus upon users in such decision-making situations both in studying and assisting them. This amounts to saying that:

1. We need alternate models of the planning and decision-making process;

2. the prospective users must play a significant role in that process;

3. therefore, the overall foci should probably not be "nation-wide," centralized projects in which the decisions must necessarily be abstract, geared to (lowest?) common denominators and remote from their consequences; but rather a variety of projects which may be centrally coordinated in a network where decision-makers will be in very close touch with the real implications of their planning;

4. research must be integrated into such planning processes. This means that research should no longer be conducted *before* a project starts, then withdrawn to leave those concerned with results often quite far from what they actually need. Research should be governed, as it were, by the problems and questions actually occurring during the course of a project. It is obvious that this demand will be difficult to meet. It will conflict most severely with traditional independence and working style of researchers, and it will create problems of logistics and coordination as it attempts to provide research services to be drawn upon when necessary.

5. Nevertheless, research itself should not be expected nor allowed to provide answers where it is, as research, not entitled to do so (i.e., in all questions that fall into the domain of value judgment, personal preference, decisions among conflicting interests and objectives, compromises, etc.).

6. This means that *research must be complemented with procedures of negotiation*: *conflict-detection, argumentation, debate, bargaining, conflict-settling. This should not be considered as a perhaps necessary evil but as the very planning process per se*, the vital source of design decision criteria, where research findings and professional technical expertise contribute to the forming of the opinion and judgment of the decision-makers, but do not substitute for it.

5. Proposals and Approaches

These are some of the things we need. Do we have the means for organizing such planning processes?

The problem of integrating research activities and research findings, reference to existing standards, codes, etc., professional expertise and interests, opinions, judgments of those concerned by a project can be viewed as an information system problem.

Work has been done recently[1] on information systems which are designed specifically to support planning processes of various kinds: Issue Based Information Systems ("IBIS") are based on a model of the planning process as an argumentative discourse during which *issues* are raised (e.g. what should be achieved, etc.) and debated because the participants in the discourse assume different positions with respect to a proposed measure.

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[1] Kunz, Werner, and Horst Rittel, "Issues as Elements of Information Systems," Center for Planning and Development Research, University of California, Berkeley, working paper #131, 1970.

Arguments are offered to back up the positions assumed or to refute counterarguments, this leading to new issues as the debate proceeds. In this play and counterplay of issues and arguments questions of fact, or explanation of definitions, causal connections or functional relationships as well as instrumental questions (how to do, achieve certain objectives technically or methodically) occur and must be answered to validate arguments. This is the task of research and professional expertise.

By choosing issues and questions as the elements or organizing principle of the information system, a very precise picture of the state of the discourse can be conveyed constantly to all parties involved in such a process--specifically to the aspects of research which are our main interest here, so that investigations may focus exactly on what is needed for the case at hand.

Arguments typically contain, implicitly, criteria for evaluation of solutions for the planning problem. Experience shows that this source of criteria is a much richer one and generates a much more differentiated discussion than pre-established evaluation systems starting from abstract categories such as "costs," "benefits," "risks." Generally, to each evaluation aspect a number of variables and indicators can be associated which may serve as performance measures for any resulting solution. Choosing among these variables again is, in itself, an issue to be handled critically, since measurements and verification involve expenditures of resources and can influence the solution itself (especially in social systems). Measurement and verification, development and manipulation of models to predict the expected performance of a solution with respect to the aspect under consideration are a matter for research and professional experts. Their business, however, is not to determine the weight an aspect should carry in the decision about a plan.

The outcome of such a process will show that whatever performance standards may have been developed a priori will never provide sufficient information for decisions to be taken in particular planning situations. In fact, they may or may not carry more weight than aspects arising specifically from that situation. This is the reason why standards should not be considered as more than a frame of reference to be constantly improved, amended and supplemented in each single case as may be necessary. If, as a result, standards lose their traditional role of legitimizing decisions, then these decisions can only be legitimized by distributing the decision-making responsibility as widely as possible by having others share the risk and consequences.

Based on such considerations and techniques, some approaches have been developed for the organization of projects (planning and research projects) which attempt to account for some of the demands outlined earlier. As an example, a proposal shall be discussed briefly which was developed for a project in Germany. The task was to survey, evaluate, recommend improvements for, and organize the implementation of prototypes of various "urban systems" proposals.

In contrast to the official proposal which was eventually given the contract,[1] the concept presented here[2] abandons the idea of extensive theoretical investigations either prior to implementation or separate from actual projects. An attempt is made to introduce the proposals in question into ongoing urban planning projects in various places at a very early stage and to initiate a "Structured Planning Discourse" (for lack of a better name) in each project which would be supported by an IBIS-type planning information system whose aim it would be to record very carefully the resulting discussions. The Structured Planning

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[1] Gerhard J. Stoeber, "Staedtebauliche Integrations-Systeme," Pilot Study, unpublished, summary in "Staedtebauliche Forschung, Kurzfassungen," May 1971 (Research projects sponsored by the German Ministry of Urban Development and Housing).

[2] Presented in greater detail in: Thorbjoern Mann, "New Approaches for the Role of Research and Information in Planning," working paper, Berkeley, February 1971.

Discourse would be organized in several distinct cycles, each with a very definite task to be fulfilled (e.g. selection of a site, spelling out and preparing the conditions for a competition, evaluating the entries and deciding on the alternatives, etc.) and each carried out with as much participation from prospective users and the public as possible.

In preparation for each cycle, a research staff would investigate "model issues" likely to be brought up and organize what contributions could be found in the literature.

During the discourse cycle itself, research assistance would be required to provide fast and expedient expertise and information on issues and questions brought up by the participants.

Subsequently an analysis of the results of the discourse would be performed and compared with results at other sites. Thus, several elements of a project in which research and planning are integrated as described, can be distinguished.(See Figure 1, SD - the various cycles of the Structured Discourse; and RA, RB, RC, the various phases of preparatory research, supporting the discourse and subsequent analysis, respectively.)

The advantages of such a project organization (besides corresponding to the demands outlined above) include:

1. the openness of the models which serve as the basis for the planning process, research, as well as the organization of the information system supporting both;

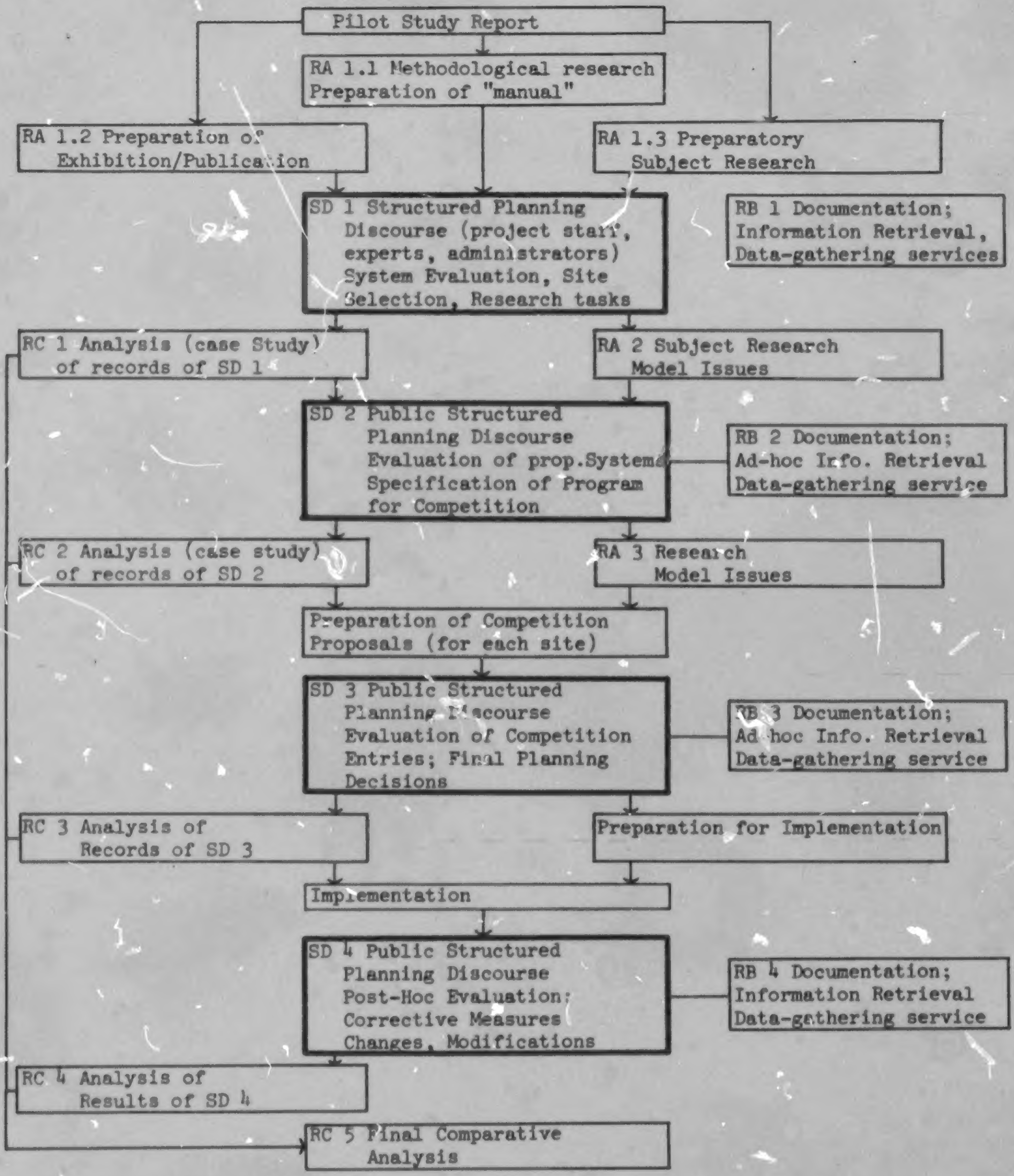
2. the possibility of comparing empirical data of separate but similar projects for the investigation of such questions as: Which aspects and problems are recurring in all projects and which ones are specific to the respective particular site and situation? What is their relative weight in the decisions that were taken in each project? From this, one might expect some information about which solutions and performance criteria may be standardized for future projects, and which ones may not.

6. Conclusion

Our contention is that the model described in Section 5 could and should be adapted to research on performance measures for industrialized housing systems and similar developments.

There are still many open questions in the development of the tools described. One of them is the validity of the assumption upon which the model rests: that the participants (or opponents) in a planning project be willing to cooperate and talk with each other about what each one perceives as the essential problems. Other questions pertain to the different role and mode of operation of the research staff within such projects, or the appropriate rule system for the treatment, negotiation, and decisions.

However, it is held that the refinement of the techniques involves the same principles as the tasks for which they will be used. The appropriate solutions will emerge by putting these techniques to work and by adapting the method to the problems as they occur and not by trying to anticipate all possible aspects and developing a fixed, perfected solution that turns out too inflexible to adapt to unanticipated obstacles.


Pilot Study Report
RA 1.1 Methodological research
Preparation of "manual"
RA 1.2 Preparation of
Exhibition/Publication
RA 1.3 Preparatory
Subject Research
SD 1 Structured Planning
Discourse (project staff,
experts, administrators)
System Evaluation, Site
Selection, Research tasks
RB 1 Documentation;
Information Retrieval,
Data-gathering services
RC 1 Analysis (case Study)
of records of SD 1
RA 2 Subject Research
Model Issues
SD 2 Public Structured
Planning Discourse
Evaluation of prop.Systems
Specification of Program
for Competition
RB 2 Documentation;
Ad-hoc Info. Retrieval
Data-gathering service
RC 2 Analysis (case study)
of records of SD 2
RA 3 Research
Model Issues
Preparation of Competition
Proposals (for each site)
SD 3 Public Structured
Planning Discourse
Evaluation of Competition
Entries; Final Planning
Decisions
RB 3 Documentation;
Ad-hoc Info. Retrieval
Data-gathering service
RC 3 Analysis of
Records of SD 3
Preparation for Implementation
Implementation
SD 4 Public Structured
Planning Discourse
Post-Hoc Evaluation;
Corrective Measures
Changes, Modifications
RB 4 Documentation;
Information Retrieval
Data-gathering service
RC 4 Analysis of
Results of SD 4
RC 5 Final Comparative
Analysis

Legend:
RA - Preparatory, general research, methodological research
RB - Ad-hoc research, expertise, information retrieval service
RC - Post-hoc Analysis Research
SD - Structured Planning Discourse
The numbers refer to the cycles of the Planning Discourse.

Fig. 1 The Structured Planning Discourse

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Application of Unobtrusive Observation Techniques in Building Performance Appraisal

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The performance of buildings is commonly measured in economic terms such as return on investment, or in otherwise readily quantifiable terms, such as amount of time required for maintenance, heat transfer, acoustic properties, or durability of materials. "Behavioral cost", which might be defined as dysfunctional aspects in the human organism caused by elements in the social and the designed environment, traditionally has escaped rigorous measurement and quantification. It became evident only through indirect indices such as statistics on pathologies, absenteeism, job turnover, etc. It is suggested that, in addition to the commonly used performance measures, building performance be based on normative user behavior that is explicitly stated in building program specifications. Several approaches to this problem area are outlined.

A performance evaluation study in a public plaza using observational techniques is reported. The findings indicate that a strong relationship exists between informal stationary activity and space defining elements in the plaza, such as benches and columns. Certain conclusions for the programming of a plaza are drawn.

La performance des bâtiments est communément mesurée en termes économiques, tels que le profit sur l'investissement, ou facilement quantifiables, comme le transfert de chaleur, les propriétés acoustiques ou la durabilité des matériaux. Le "coût réactionnel", qui peut être défini comme la perturbation fonctionnelle d'un organisme humain causée par des éléments de l'environnement social et résidentiel, a traditionnellement échappé à la mesure et à l'estimation strictes. Il se révéle seulement par des indices indirects comme les statistiques sur les pathologies, l'absentéisme, les changements d'emploi, etc. On propose qu'à côté des mesures de performance d'usage commun, la performance dans la construction soit fondée sur le comportement normatif de l'usager, exprimé explicitement dans les spécifications de programmes de construction. Plusieurs méthodes d'approche de ce problème sont résumées.

On décrit une étude d'évaluation de performance sur une place publique, qui utilise les techniques d'observation. Les résultats indiquent qu'un étroit rapport existe entre l'activité stationnaire courante et les éléments qui accentuent l'espace sur la place, comme les bancs et les colonnes. Une analyse de comportement dans les marchés couverts est résumée. Certaines conclusions pour la conception d'une place publique en sont tirées.

Key words: Behavioral cost; building performance; cultural context; unobtrusive observation; user behavior; user feedback.

1. Introduction

User-environment evaluations, and consequently design programs based upon them, have to account for the cultural context within which they are conducted. Certainly both the use of space and the design of the physical environment are dependent on cultural conventions. As in fashion, behavior can be judged to be appropriate or inappropriate, depending upon the social context in which it occurs. Thus, an empirical base has to be developed in which the relationships between behavior and the elements of the designed environment can be studied in terms of their social context. Such an empirical base would provide the information necessary to minimize the occurrence of stress and "dysfunctional behavior" (behavior which is inappropriate in a particular cultural context) which could result from the designed environment. This paper describes the importance of behavior-based design criteria as a precondition for user-relevant programming and design of buildings.

The need to bridge the gap between programming criteria for physical environments and predictable behavioral outcomes is recognized. Examples of research, particularly unobtrusive observation techniques, are reported in which methods of gathering behavioral data related to the physical environments have been developed.

2. Human Performance Measures

With regard to desired user behavior outcomes, the building performance concept must include two components if the system is to function properly:

1. Performance criteria which are determined by the goal structure of a particular system.
2. Specifications which describe the way to achieve the desired performance of the system.

The importance of performance evaluation feedback within the architectural "systems framework" has also been pointed out by Handler[1][1] He identifies two basic dimensions of performance:

1. The technical and environmental performance measures, which include the performance of structures, mechanical systems, and materials in buildings.

2. Human performance measures, that is, the effect of buildings on the behavior and performance of the users. This includes the health, well-being, and task performance of people. Handler set forth the measurable variables of human performance as follows:

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[1] Figures in brackets indicate the literature references at end of this paper.

1. Health
    - body temperature
    - metabolism and heat loss
    - heart and pulse rate
    - respiratory rate
    - blood pressure
    - sweat point
    - muscular effort and tension
    - infection
2. Sensory and perceptual alertness
    - sight
        - light sensitivity
        - brightness discrimination
        - visual acuity
        - depth and movement perception
    - hearing
        - loudness sensitivity
        - pitch discrimination
        - intelligibility
    - smell
        - sensitivity
        - discrimination
3. Well-being
    - thermal
    - visual
    - auditory
    - olfactory
    - tactile
    - fatigue
4. Task effectiveness
    - speed
    - accuracy
    - output
        - quantity
        - quality
    - efficiency
    - human cost
5. Group behavior
    - interaction
    - task effectiveness

These measures hardly account for "human" or "behavioral cost", i.e. the effects of higher order and complex causes connected with buildings. For example, the connotative meanings which may be attached to buildings, due to historical, religious or other events that took place in them, can be said to contribute to their symbolic performance. Certain buildings have become the object of pilgrimages in the hope of miraculous healings and similar effects upon the visitors.

The need of introducing evaluative information into the design and planning process on the relationship between human requirements and the physical environment was stressed by Bjorkto, et al. [2] at the 1971 CIB meeting. They advocated research into user preferences, characteristics, and activities as they were supported by the designed environment. In another evaluative study, Twichell [3] devised a scoring system for performance appraisal which intended to measure the equality of housing. In this system dwelling appraisals and environmental surveys using interviews and observational techniques established factual data on housing. A panel of housing experts then compared these data with accepted housing standards, dealing out negative scores where deficiencies were found.

In an attempt to define performance terms for mental health facilities Brill and Kraus [4] developed sets of continuum scales on which participants would rate the characteristics of settings for human activity according to the following sets of performance characteristics:

PC 1	Communality	Privacy
PC 2	Sociopetality	Sociofugality
PC 3	Informality	Formality
PC 4	Familiarity	Remoteness
PC 5	Accessibility	Inaccessibility
PC 6	Ambiguity	Legibility
PC 7	Diversity	Homogeneity
PC 8	Adaptability	Fixity
PC 9	Comfort	Discomfort

Each PC is a continuum with no values ascribed to either end. For example, two different physical settings may require extreme privacy or open communality and either will be considered a positive value for that setting.

A new basis for architectural programming, according to Studer and Stea [5] would be behavioral performance specifications for rooms and buildings. Instead of using existing labels like "classroom" of a certain size, the activities and their behavioral-environmental requirements would be spelled out in detail in order to achieve a better fit of behavior and design. In a further elaboration, Studer [6]--with a model of the design process called "the dynamics of behavior-contingent physical systems"--attempted to provide a general theoretical framework for environmental design based on Skinner's principle of operant conditioning. In essence this model shows the importance of the following: Performance appraisal, i.e. empirical evaluative research, the establishment of behavioral goal specifications in environmental design, the simulation of alternative solutions and the testing of their effects on user behavior.

Although lip service has been paid to the inclusion of the social cost in the performance appraisal of buildings, e.g. housing [7], few serious attempts (other than the ones mentioned previously) have been made in the past to specify building performance in behavioral terms. Therefore, behavioral indices have escaped rigorous measurement. When measurement was done, qualitative subjective evaluations were found unreliable, and quantitative behavior analyses presented great difficulties. It can be said that if the designed environment is to support and permit culturally determined desired behavior to occur, then an understanding must be gained of those laws and mechanisms that govern man-environment relationships. Then generalizations can be made for the purpose of future design applications and predictions of implications. Therefore, it is necessary to investigate systematically and empirically the structure of man-environment relationships, what their components are, and which of these--for the designer's benefit--refer directly to the designed physical environment.

The field of architectural psychology is in a preparadigmatic stage of its development. The studies presented here are some of the attempt which have been made to create conceptual models for the study of man-environment interaction. No comprehensive theory of man-environment relations exists at this time. The various concepts represent at best partial theories capable of explaining certain aspects and lawful relationships between behavior and environment. Seen in this context the observational study which follows aims at an investigation of the role which designed features of a public plaza play in supporting occurring behavior. Thus, a preliminary conceptual model is generated which states that artifacts are surrounded by a field of attraction or influence within which certain categories of behavior are most likely to occur.

3. Observational Techniques

This paper reports on an attempt of performance appraisal through observational techniques, namely simple observation, mapping, quantitative and qualitative analysis of user environments. The setting for the study, carried out in May and June of 1971, was a public plaza in front of the student union building at Virginia Polytechnic Institute and State University. The purpose of this project was to investigate the use of various parts and designed features of the plaza, in particular, the types, amount and locations of occurring behavior. Certain hypotheses were based upon previous studies of behavior in public places which stated that elements of the environment are actively used by persons engaging in a range of specified categories of behavior which are appropriate for the context. Further, evidence of the supportive role of physical artifacts can be given by qualitative and quantitative analysis of behavior.

Unobtrusive observational techniques were developed in order to systematically record human behavior as it occurs in a public plaza. These techniques include:

1. Direct observation and establishment of a behavior repertoire for the setting.
2. Standardized data sheets for recording coded behavior categories, body posture, interactional patterns, time, etc.
3. Maps for recording spatial-location data on individual subjects and groups in the plaza.
4. Video-tape recordings for time-sampled observations of the setting.
5. Quantitative analysis of recorded data, computation of frequencies, standard deviations and means for occurring behavior categories.
6. Correlations between frequencies of behavior categories, mapped locations and distance zones were planned.

Emphasis in the data evaluation was on characteristics of stationary activity in the plaza vs. movement patterns, particularly on interactive behavior. Preliminary findings of the study indicated: Most interaction whether in small or large groups occurs on or in very close proximity to physical artifacts, such as benches, stairs, railings and columns, but not in open and "undefined" spaces. Further, interaction tends to take place "where the action is", i.e., generally near interest generating places (e.g., view) of high user intensity. As a result of the study, some criteria for plaza design were developed. Due to lack of space only a sketchy description will be given of the steps outlined above.

Basic to the construction of a standardized data recording sheet was the establishment of a behavior repertoire for the plaza. Observations of the setting were made for two full days and observed behavior episodes were described. These behavior episodes were then grouped into distinct observable behavior categories, such as stationary behavior or movement, which then was broken down further into more subtle units describing body posture and activity the subject was engaged in. The data sheet (see sample in the appendix) for the observation of the plaza was designed to record three basic dimensions of ongoing activity:

1. The temporal dimension, i.e., the time of occurrence, the frequency and duration of behavior events.
2. The spatial dimension, i.e. the locational data on stationary events as well as moving subjects.
3. The behavioral dimension, i.e. body posture, type of activity, etc.

In addition, due to the limitations of unobtrusive observation, only the numbers and sex of the observed subjects could be identified and recorded. For events not provided in the preestablished categories of the data sheets, a "comment" column allowed for additional remarks to explain the situation under observation. The data sheet was broken down into two parts to record essentially different kinds of information:

1. A data sheet was designed for recording behavioral categories which included the following: walking, running, riding, talking, study, eating, solitary-nonactive, playing. Postural categories: sit, stand, lying, leaning, kneel, squat. Additional categories included: date, time, weather, temperature, observer, observation number, coded location of observed event, number of subjects observed and their sex.
2. A gridded map of the plaza was provided for location observation. A grid pattern in the pavement of the plaza aided in identifying locations of subjects. In addition to the locations and groupings of subjects, their directions of movement and their sex was recorded on the mapping part.

Observations of the plaza were made by 4 students of architecture. For the low activity periods it was sufficient to have one observer record all ongoing activity in the plaza, e.g. during the morning and early afternoon hours. Thus, the observers worked in shifts of one to maximum of two hours at a time. In particularly active time periods such as the lunch period and early evening hours it was necessary to have two or more observers record simultaneously the behavior in different parts of the plaza, e.g. it was often divided into two halves for the purpose of observing both stationary and movement behavior at five minute intervals. This amount of time was found necessary in order to record the locations of subjects on the map and to fill in and check the respective behavior categories on the data sheet between observation times. Thus the attempt was made to capture as in a "frozen picture" the behavior in the plaza at a given point in time. For each observation time a new data sheet was used and coded accordingly.

Observers recorded so called "behavior events" which were the basic unit of spatial-locational analysis. A behavior event was defined as any individual or group occupying space in the plaza at a given observation time and the events were recorded as such, i.e. as solitary or interactional units made up of one, two or more subjects. Observations amounted to a total of 17 hours and 20 minutes over a period of three weeks during pleasant weather conditions in spring quarter. During this time 1003 behavior events were observed, with the time sample being very limited. However, every daytime hour and weekday was at least represented once in the sample. Observers were stationed as unobtrusively as possible behind shrubbery across the street from where a good overview of the plaza was possible. As means of learning about the plaza and its movement flow super-8 time-lapse recordings were made initially, as well as some video-tapings, including interviews of plaza users. However, for the purpose of this study direct observation was the major method of data collection.

Although it may not be justified to draw conclusions and to generalize from one case study alone, some of the observed phenomena which had been found previously by other researchers were confirmed in this project. Since intuitively any designer of a plaza would base his decisions on the suspected effect of physical arrangements on user behavior, other findings seemed quite obvious, e.g. the arrangement of benches and planters and their effect on stationary and interactional behavior. Relationships between spatial behavior and physical artifacts have been documented in quantitative and qualitative terms by researchers like Sommer [8], Barker [9], Esser [10], Stilitz [11], Wolff [12], de Jonge [13] and Hutt [14], who all employed unobtrusive observational techniques for data collection.

In attempting to judge the quality of a plaza or parts of it, it would seem important to be able to specify not only the desired behavior categories but also the amount of each desired for a particular setting. In this study, however, value judgements have generally not been made regarding the "goodness of fit" of certain design elements in the plaza. Instead, the objective was to report on any relationships that might exist, whether good or bad, between elements of the plaza and occurring behavior.

4. Results

Mapped data were compiled separately for movement and stationary events in order to determine the locations and frequency of occurrence of these two basic behavior categories. From the movement data, although recorded as discrete events, it became clear where the major traffic routes were located. The mapped data on stationary activity, an example of which is included in the appendix, show that it most frequently occurs on or near physical artifacts in the plaza.

From the data sheets frequencies were computed for the use of various locations in the plaza, as well as the frequency of occurrence of each behavior category and group size. The data will not be discussed in detail here. A summary is given in the appendix.

4a. Interaction in the Plaza

The hypothesis that physical artifacts are actively used when persons engage in social contact was supported by the findings. Interactive behavior occurred almost exclusively on or near benches, planters, columns, railings, park meters and stairs. To offer an explanation for this phenomenon can only be speculation at this time. It appears clear, however, that interacting subjects, whether they were standing, sitting or leaning, needed some psychological hold or reference object which allowed them to carry on a conversation in the midst of pedestrian traffic consisting mostly of strangers. Thus it was found that within a radius of 2 to 3 feet around an artifact most interactions would occur and that subsequently the degree of attraction and with it the frequency of interactions decreased with increasing distance from the artifact. The attracting or repelling effect of artifacts on certain user behavior is depending upon the cultural context and socially accepted norms of the use of the environment. The studies by Stilitz and de Jonge cited earlier contain findings which point to environmental attributes such as "traversability, connectiveness and containment" or "edge effect, focal points, island effect and polarization effect". Seating facilities can be arranged in such a way as to encourage interaction or to prevent it. The low number of interactions observed in groups of more than two persons could be explained by the following: distances between planters (which were combined benches) were too great to permit verbal interaction among users facing each other; the sight lines were continuously interrupted by people moving between the planters; the square form of the planters made people face away from each other. As the only seating facility in the plaza and being situated in the traffic flow from the front stairs to the building entrance, the planters were not suited to facilitate interaction in larger groups. Benches should have been placed in a protected "pocket" of the plaza where interference from traffic could be minimized.

4b. Solitary Behavior in the Plaza

Facilities placed in "protective pockets" would be even more important for activities like studying and eating. (These activities were found to be almost entirely absent from the plaza. Generally, in the park areas this university does not provide benches or other seating facilities. The reason given for this by the administration is that littering behavior must be discouraged.) Facilities for solitary activity in the plaza were found to be extremely few. Two types of solitary activity could be differentiated: solitary-active and solitary-nonactive. In the first case an individual would use a sheltered place to withdraw from pedestrian traffic and interference in his activity, e.g. reading, resting, eating, etc. In the second case stimulation for the individual would not come from within the person, i.e. his motivation to engage in a particular activity, but from the environment, such as an interesting view. Only the second type of behavior was found in the plaza, mainly on the stairs and the fronts of the planters facing the sidewalk and street. Columns, railings and planters served as "containers" for waiting individuals. However, the open areas of the plaza which had no space defining elements which users could relate to in their activities were hardly used (areas B, C, D and L, M, N) and the covered and somewhat dark parts of the plaza were not used at all for stationary activity.

4c. Movement in the Plaza

As might be expected, movement patterns followed the most efficient paths between entrances and connectors of the plaza, i.e. stairs and doors leading into the building. No clearly defined zones were reserved for movement of pedestrians and therefore conflicts with the stationary activities resulted. In planning the plaza wrong assumptions had been made about the amount of traffic and the direction from which it would enter the plaza. For example, about equal numbers of users were found to enter from three major directions: downtown, campus and the street. However, while only one fifth (the J/K section) of the extremely wide stairway (so designed for esthetic reasons) was actually used, the other two stairways leading to downtown and campus appeared to be overloaded and too small.

4d. General Evaluation of the Plaza

Spaces and facilities for movement and stationary behavior were not separated and therefore, confusion and spatial interference occurred in some parts of the plaza whereas others were not used at all. Moving benches and places for interaction out of the major traffic flow into more sheltered areas would have made the spatial distribution of subjects more even. The number of subjects using benches and planters decreased with increasing distance from the major pedestrian traffic flow. Only a very limited number of behavior categories was found in the plaza. For example, eating (12) and studying (17) are almost nonexistent considering that 1003 events were observed. To achieve a richer and more lively environment, it would appear appropriate to provide choice between places for privacy as well as vehicles to faster communal activity. In most (43%) of the observed events there were individuals, followed by dyads (34%), however, groups of 3 or more accounted for only a fraction of ongoing behavior. As a place for larger informal group activity and focal point for gatherings this plaza fails, whereas other locations on campus which were not specifically designed for this purpose fulfill the role of informal outdoor meeting places.

5. Conclusions

Nonreactive methods of data collection focusing on overt behavior can be applied advantageously to performance appraisal of the built environment, in particular, to user intensive buildings and spaces such as subway stations, lobbies of public buildings, etc. The user behavior in such facilities can be monitored by hidden hardware or through direct observation techniques. Quantitative analyses of the recorded data can be made by computing frequencies of occurring behavior categories, means, standard deviations and correlations. Thus, information can be gained on the following:

a. Amount and types of ongoing behavior in buildings, i.e. a profile of existing behaviors.
b. Time distribution of different activities carried out in public places and in buildings, i.e. a profile of intensity of parts of buildings usage.

c. Locational-spatial characteristics supporting observed behavior, e.g. conditions under which waiting or informal interaction takes place.

d. Conflict situations and their sources, e.g. parts of spaces where users tend to get lost because of disorientation, bump into each other, misinterpret windows for openings, to name just a few examples.

e. "Appropriateness" of observed behavior, e.g. whether the behaviors supported by a public plaza are compatible with the goals set for the particular context. For example, it can be observed whether the amount of interaction among users can be facilitated by such an arrangement exceeds the limits appropriate for the context, as prescribed by social and organizational norms.

A basic requirement for the type of performance appraisal advocated here is the explicit statement of goals, in the form of behavioral performance criteria of the type of space or building under investigation. These criteria are dependent on the socio-cultural context within which a building exists. Empirical evaluation of existing buildings will help create such performance criteria by gaining user feedback from well-functioning environments through the application of complementary verbal and observational measurement techniques.

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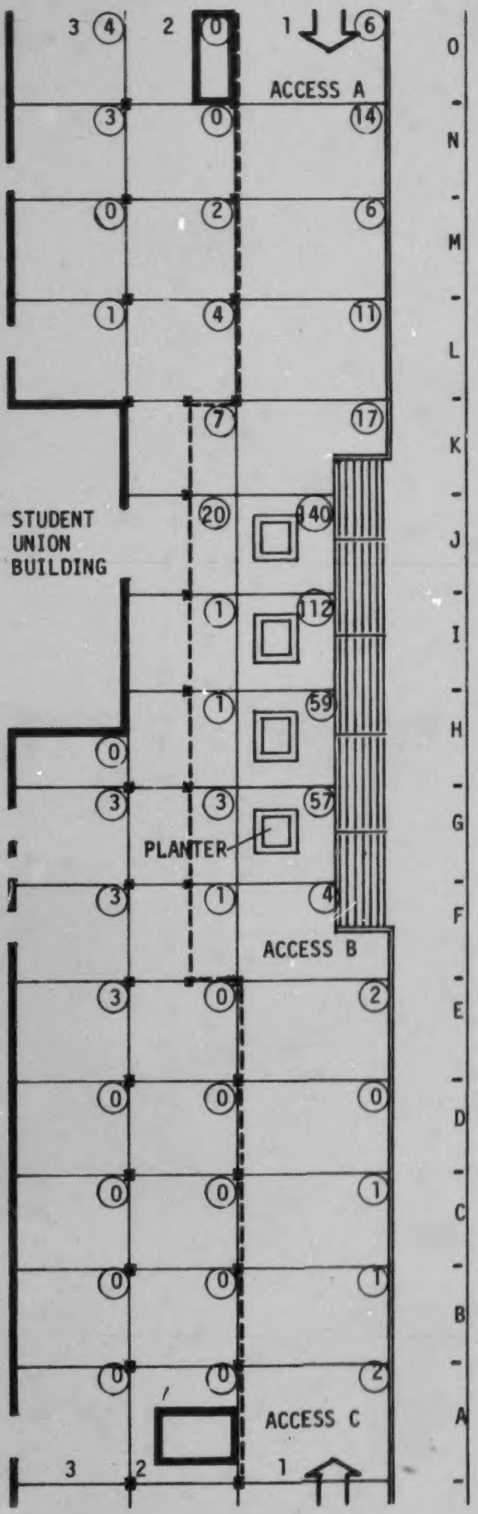
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DATA SHEET AND LAYOUT OF THE PLAZA

Left: Example of mapped data for stationary activity.

Below: Standardized data sheet with a summary listing of stationary events (Col. 9-19)

OBSERVER: TEMPERATURE:
DATE: WEATHER:
TIME:

1	OBS NO.					
2	LOCATION					
3	# SUBJECTS PER EVENT	1 211	2 167	3 64	4 21	≥5 24
4	MALE					
5	FEMALE					
6	WALKING	----				
7	RUNNING	----				
8	RIDING	----				
9	TALKING	255				
10	STUDYING	17				
11	EATING	12				
12	SOLITARY NON-ACTIVE	115				
13	PLAYING	0				
14	SITTING	369				
15	STANDING	147				
16	LYING	3				
17	LEANING	34				
18	KNEELING	1				
19	SQUATTING	4				
20	COMMENTS					

Total observation time: 17 hrs. 20 min.
Total # of observed behavior events: 1003
Total # of stationary events: 489
Total # of movement events: 514

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Verbalized User Response and the Building Performance Concept: A Case Study in University Residence Hall Evaluation

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Building performance appraisal focused upon user behavior is a recognized need. Theoretical frameworks exist for the analysis, programming and design of buildings with human behavior as the basic unit of analysis, particularly with reference to normative states of equilibrium within a given cultural and environmental context. These states may be expressed in terms of user satisfaction through verbalization. Based upon Thurstone's scale of equal-appearing intervals, an evaluative tool for the qualitative assessment of building performance has been developed. The method attempts to measure the subjective importance and acceptance of features of the built environment by the users. The data thus derived may complement traditional 'hardware' criteria in the appraisal of buildings. The evaluation procedure, consisting of six steps, was applied to students living in residence halls at Virginia Polytechnic Institute and State University:

1. Construction of Attitude Statements.
2. Selection of Statements.
3. Scaling of Attitude Statements.
4. Statistical Evaluation.
5. Selection of "Best" Scoring Statements.
6. Validation Procedure and Construction of Comparative Response Profiles of 3 Residence Halls.

Some conclusions resulting from the building evaluation are outlined for consideration in future programming of residence halls.

L'évaluation de performance dans la construction concentrée sur le comportement de l'usager est un besoin reconnu. Des cadres de référence théoriques existent pour l'analyse, la planification et l'étude des bâtiments avec, comme unité de base de l'analyse, le comportement humain, en particulier en ce qui concerne les états normatifs d'équilibre dans le contexte d'un milieu culturel donné. Ces états peuvent être traduits en termes de satisfaction exprimée verbalement par l'usager. On a développé une méthode d'évaluation pour l'estimation qualitative de performance dans la construction, fondée sur l'échelle des intervalles égaux de Thurstone. La méthode s'efforce de mesurer l'importance subjective et l'acceptation de traits de l'environnement du bâtiment par les usagers. Les résultats ainsi obtenus devraient compléter les critères traditionnels "matériels" dans l'évaluation des bâtiments. La méthode d'évaluation, en six étapes, fut appliquée à des étudiants vivant en cités universitaires à l'Institut Polytechnique de Virginie ainsi qu'à l'Université d'Etat:

1. Interprétation des "déclarations d'attitude"

2. Sélection des déclarations.
3. Graduation des déclarations d'attitude.
4. Evaluation statistique.
5. Sélection des "meilleures" déclarations d'après leur notation.
6. Validation de la méthode et élaboration de profils comparatifs des réponses de 3 résidences.

On a résumé les conclusions résultant de l'évaluation de la construction afin de les utiliser dans les programmes futurs de maisons d'étudiants.

Key words: Attitude scale; building performance; comparative user response; user behavior; user satisfaction; verbalized response.

1. Introduction

Environmental psychology, the current and developing focus of environmental research, has established methodological techniques of correlating observed behavior and verbal responses of the users of environments. For example, time-lapse photography and structured interviews have been employed to determine patterns of behavior within a particular setting. Such methods have furnished useful information, and they indicate the yet unexplored potential of photography in the field of behavioral studies especially those related to the evaluation of building performance. This fact has also been pointed out by Robert Sommer [1][1] in numerous writings describing experiments which demonstrated how the observed behavior of building users was affected by the design.

Methods of evaluating performance of buildings are geared toward measurement of human means of expression, i.e., quantitative and qualitative evaluation of responses such as speech, writing, drawing, physiological reactions and acts of movement. Vander Ryn [2] critically examined certain "methods of evaluating building performance" and described merit and pitfalls of the following established social research techniques:

1. Observation
2. Structured and unstructured interviews
3. Activity log
4. Literature search

These methods concentrate on two major means of human communication, i.e. verbalized attitudinal response and observable overt behavior. Comparison and analysis of all data obtained from the various sources of information can help understand the interaction of patterns of behavior and variables relevant to physical design. They may even lead to the identification of issues of concern, i.e. fit or misfit within a building.

Design-related information expressed by the research subjects often has been the major user input into the design process.

2. Verbalized Response to Environment

Verbalized response measurement can describe certain dimensions of environmental experience, and therefore this medium is widely used in the design profession for gathering relavant data on the performance of existing environments. Some of the techniques of evaluation and measurement of user responses have been examined by Henry Sanoff [3] for their applicability in various situations. Canter [4], Hershberger [5] and others developed scaling techniques in which aspects of buildings are described by sets of bipolar adjective scales. They can evaluate the degree of perceptual agreement of designers and users of an environment. Canter's appraisal techniques are based on Osgood's [6] method of the "semantic differential" for the measurement of meaning. This method uses factor analysis to determine:

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[1] Figures in brackets indicate the literature references at end of this paper.

> the number and nature of factors entering into semantic description and judgment, and the selection of a set of specific scales corresponding to these factors which can be standardized as a measure of meaning.

Osgood points out that the method might possibly be applied to measure esthetic properties of an environment.

Fechner's [7] research is also significant in that it attempts to quantify and measure esthetic dimensions as they are perceived by subjects. In his experiments with the subjective judgement of differently shaped rectangles , the concept of 'Wohlgefalligkeit' (pleasantness) was introduced which described the preferences (e. g., for shapes approximating the golden section) of the subjects. Accordingly, the unit called 'Lustquantum' was a measure representing enjoyment and pleasure evoked by a display of rectangles in the respective group of tested people. The implications of Fechner's experiments are that at a certain level of abstraction, subjects are capable of judging the degree of relevance, enjoyment and preference of particular characteristics of the environment. Scaling techniques have found a wide variety of application to attitude measurement with regard to building design. In particular, the work of Thurstone [8] on Fechner's Law and the method of equal-appearing intervals in the construction of attitude scales was the point of departure for the author's preliminary performance evaluation of university residence halls.

3. Methods

The first step of the experiment had the purpose of identifying environmental issues of concern to the users of residence halls at Virginia Polytechnic Institute and State University. A sample of 157 students, consisting of three classes of students attending an introductory sociology course, was chosen. These subjects were 90% male, representing all major fields of study, and 95% were living in residence halls at the time of this experiment, i. e. in the fall of 1968. Although most subjects were sophomores, all undergraduate class levels were represented.

In a first unstructured session subjects made comments on aspects of university life which they felt favorable, unfavorable, or indifferent. More than 2,000 statements were obtained from the subjects in this session on attitude statement construction many of which expressed attitudes toward the physical residence hall environment. The statements were categorized and grouped into approximately 100 distinct content areas. These content areas represented a cross-section of all attitudes and were extracted from the topics occurring most frequently in the subjects' statements. The major criterion for the inclusion of a statement of a particular content category was that it must clearly reflect conditions in residence halls as they were experienced by the inhabitants. Unsuitable statements were discarded if they did not refer to dormitories and their impact on the users.

A similar sample of subjects as in the first step was used in the second step of the experiment, i. e. 5 different classes totalling 191 students, 95% of whom were living in residence halls at the time of the experiment. The subjects were asked to rank the 100 content areas constructed in the first part of this experiment. Attitude statements were read to the subjects, who were then asked to place these statements on an 11-point continuum, ranging from undesirable (-5) to desirable (+5) features. The position at which a subject placed a statement on the attitude scale was to reflect the importance or degree of relevance that the aspect or feature expressed in the statement had for the subject. During the scaling sessions an equal number of positive and negative statements was presented in random order.

The statistical analysis included calculating the mean, standard deviation, and frequency distribution for each of the ranked statements. This established which issues were the most important ones, as agreed upon by the majority of students in the sample. Examples of the graphic representations of the students' judgements for selected statements are given in the appendix.

In order to validate the method as a comparative evaluation tool, 25 attitude statements approximately representing all points on the continuum (-5 to +5) and having generally received high agreement among the student judges were selected to be included in a validation questionnaire (see appendix, Table 1). This questionnaire was administered to 295 male subjects in a 20% occupancy sample of three different sized residence halls, i. e. Hall A: N=57 , Hall B: N=68, Hall C: 170 respondents. Since the objective was to compare the quality of residence halls on the basis of 25 selected issues, the decision was made to exclude womens' residence halls since they differed too much from the mens' residence halls in layout, comfort, and physical design to allow for comparative evaluation. The questionnaire was distributed and collected by student resident advisors on the basis of room numbers determined from a random table. The respondents were asked to judge whether the items in the questionnaire applied to their residence hall or not. In the author's judgement there were distinct qualitative differences in the three chosen residence halls, as expressed in the comparative profiles contained in the appendix.

4. Results

The attitude statements made by the users of residence halls could be grouped into the following categories:

1. Physical - environmental features
   a) Rooms and immediate environment of students
   b) Total residence hall environment and its surrounding area
2. Psychological - behavioral features
   a) Performance criteria of the subjects
   b) Life 'enjoyment' criteria
3. Sociological features
   a) The student's social interaction with friends and neighbors
   b) The network of relationships within and among residence halls
4. Administrative features and regulations

Evaluation of the attitude statement construction session showed that most statements dealt with physical features of residence halls. Several positive features were mentioned, such as the availability of individual sinks within the students' rooms, water fountains, candy and coke machines, elevators, the small size, and the appearance of the exterior of dormitories. Social aspects such as "bull sessions," making new friends, sense of togetherness, and meeting different types of people were also mentioned quite often.

Among the negative statements, physical features were most frequently mentioned. These included extremely poor acoustics, monotonous and poor design in general, long and noisy hallways, the institutional character of residence halls, drab and depressing appearance of materials used, lack of recreation facilities and inadequate study spaces, insufficient sizes of rooms (and therefore lack of privacy), and features such as inconvenient bunk beds, bad lighting, and insufficient shelf and closet space. Desire to liberalize and to change residence hall regulations were also frequently expressed. Complaints about regulations pertained mainly to the prohibition of alcoholic beverages, hot plates, refrigerators and air conditioners in dormitories. The unavailability of a choice among different kinds of housing for undergraduate students was not criticized as much as the lack of university housing for graduate and married students.

The list of 25 statements used in the validation procedure can be found in the appendix (Table 1). The results of this questionnaire were converted into percentages of 'agree' or 'disagree' responses representing judgement profiles of the 3 residence halls (see examples in Figure 2). Some of the statements represented in Figure 2 (Comparative Profiles of Some Qualitative Judgements of Three Residence Halls) will be discussed here. It should be noted that the degree of importance of the judged feature decreases as the midpoint of the scale is approached from the two extreme scale positions (-5 and +5).

In the bar graph representation of responses the left half concerned with undesirable features which did not apply to the respective respondent's residence hall has been worded in such a way that the profile for the residence hall with highest quality will be highest, as does the right half of the graph which represents desirable features which applied to the respective respondent's residence hall. Accordingly, residence hall B (Vawter, 340 residents) ranked highest in quality if compared with residence hall A(Monteith, 285 residents) and residence hall C (Lee, 850 residents). 11 selected statements follow:

1. No. 98: "From the outside, my dorm looks like a jail" clearly differentiates 82% of the students in Dorm B who believe it does not look like a jail, from the 62% in Dorm A who agree with the statement.
2. No. 33: "The floor material of my room looks very ugly." In the oldest dorm, A, 92% agree, in the second oldest, B, 57% agree and in the newest and largest dorm, C, only 40% believe that their floor is ugly.
3. No. 46: "In my dorm orientation is poor" applied to 42% of the students in Dorm C only 18% in Dorm B and 33% in Dorm A.
4. No. 60: "The corridors in my dorm are too long" was disagreed with by 82% in the freshman Dorm B, whereas, 46% in Dorm C believed that this statement applied to their residence hall.
5. No. 11: "The halls in my dorm create a sense of unity among the residents." 78% in Dorm B (Freshmen only) agree with this statement; however, 74% of the residents of the largest Dorm, (Dorm C, students from all but freshmen class levels) cannot agree. In Dorm B which houses only upperclass men and which is relatively small in size 60% agree that the halls in the dorm help create a sense of unity. It appears that the size and the mix of students of different class levels influence the number of acquaintances or conversely the number of strangers the residents will meet in the hallways.
6. No. 2: "The exterior of my dorm is very pleasing to the eye" was included to check the responses of statement No. 98. In Dorm A only 5% agree, whereas in Dorm B, 67% agree and Dorm C, 48%.
7. Almost everybody in all 3 dorms agrees to Statement No. 59: "Without personal decorations, the barrenness of my room is distasteful."
8. According to the response Statement No. 100 "There is a lack of entertainment facilities in my dorm," all three dorms need major improvements regarding this issue, as shown by about 90% agreement in all 3 cases.
9. Almost everybody in all 3 dorms disagreed with statement No. 8. "The lounge of my dorm is attractive."
10. No. 86: "Many rooms on a corridor lead to frequent disturbance through friends dropping in" was agreed to by about 75% of all students.
11. Almost everybody agreed that the furnishings in all dorms were very dull (No. 29) and very few students believed that the interior of their dorms look pleasant (No. 85).

Lack of space only permits a summary listing of pertinent criteria which evolved from this evaluative study of residence halls:

1. The individual student's room: A choice among differently sized, equipped and priced rooms for single and multiple occupancy must be provided, in order to meet the students' changing needs over time. Flexibility in furniture arrangements is extremely important, as is the ease with which personal items and decorations can be brought into rooms. Individual control over the thermal environment ranks highest among desirable features.
2. The arrangement of students' rooms: In a pilot study on sociometric choices it was found that with the exception of freshmen, most students would like to live in groups not larger than 8-12 individuals. This figure coincides with the average number of friends reported by the students. "Groups: of 60 students may seem reasonable from an administrative or maintenance's efficency point of view; however, usually only casual contact is possible among such a large number of students. At least one third of all students prefer suite-like arrangements of rooms to the conventional double-loaded corridor type with its many disadvantages, such as noise problems, institutional appearance and sources of disturbance. These smaller groups of room arrangements also lead to greater flexibility in terms of changing uses. They should have shower and bathroom facilities, a kitchenette, a common congregation area and possibly a study area separate from the individual rooms. Independent access should be given to each group of rooms.
3. The arrangements of residence halls: Residence halls with 1,000 and more students each are too large if they are not broken down into smaller parts. High density

low-rise, walk-up residence halls are preferred to high-rises standing isolated within large open spaces. 250 to 300 students per building is acceptable. High-rise dormitories are acceptable, provided an appropriate grouping of rooms and activity areas with easy access has been achieved. Apart from the properties described above, excessively long corridors (200-300 feet) create an institutional feeling among students. Although lighting generally is sufficient, an impression of sterility is evoked in the person walking through them. Orientation is also often difficult within the residence halls. From the results of the study, the architectural appearance of residence halls at VPI leaves much to be desired. Although impressive stonework has been used they apparently give the impression of jails.

5. Conclusions

The degree of importance of features of the environment as perceived by individual users was measured by adapting the Thurstone scaling technique. The response to the physical environment by larger groups of users can be measured particularly well in institutional settings. Thus, a hierarchy of priorities regarding acceptance or rejection of environmental features can be established. Because performance criteria obtained through the method of relevance scales are characteristic of the particular environment and subjects under investigation, great caution has to be exercised if results are to be generalized to other populations in culturally different locations, such as a campus located in a large metropolitan area vs. a campus in a rural area.

In light of cultural variations in the use of space and facilities, the relative scale of performance criteria would have to be developed specifically for the characteristics of each setting under investigation. In conclusion, the method described in this paper aims at the qualitative assessment of the built environment by its users. It allows for the identification of user concerns relevant to different strata of user groups. The expressed and measured degree of acceptance or rejection of features of buildings thus reflects their performance.

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7. Appendix

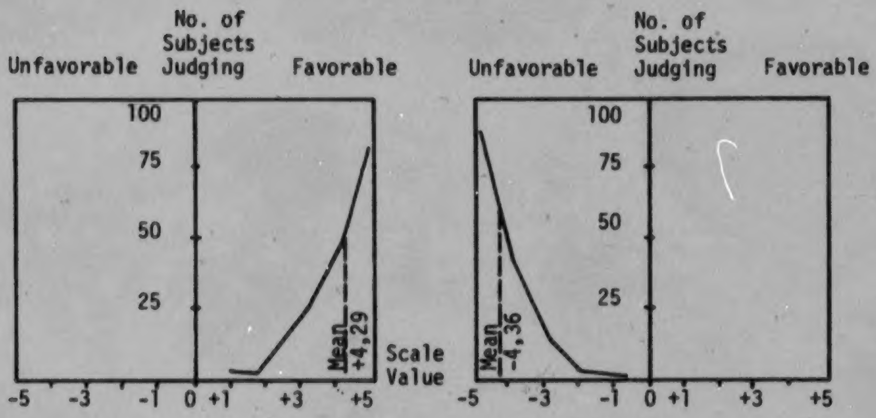
Table 1

Means and Standard Deviations of the 25 Statements Which Were Included in the Final Validation Questionnaire (in Mean Rank Order)

Statement Number	Mean	S. D.	Statement
99	1.6486	1.2337	1. There is no ventilation in my room.
84	2.1351	1.9679	2. In my room, noise can be heard from two or three doors away.
59	2.2770	1.6488	3. Without personal decorations, the barrenness of my room is distasteful.
100	2.4459	1.2469	4. There is a lack of entertainment facilities in my dorm.
98	2.7838	1.5974	5. From the outside, my dorm looks like a jail.
72	2.9388	1.9523	6. The rooms in my dorm are unvaried, monotonous boxes with little stimulation.
29	3.1014	1.7330	7. The furnishings in my dorm are very dull.
1	3.3767	1.3500	8. The size of my double room makes it difficult to maintain order.
33	3.5946	1.8620	9. The floor material of my room looks very ugly.
24	3.9662	1.8532	10. My sink is placed badly.
86	4.1554	1.9049	11. Many rooms on a corridor lead to frequent disturbance through friends dropping in.
46	4.2770	1.8874	12. In my dorm, orientation is poor.
60	4.5473	1.7275	13. The corridors in my dorm are too long.
68	4.7770	1.7254	14. My hall is too big to let me feel at home.
18	7.2635	1.7742	15. The arrangement of our dorm rooms along a corridor is satisfactory.
11	7.5724	1.7390	16. The halls in my dorm create a sense of unity among the residents.
2	7.8571	1.7866	17. The exterior of my dorm is very pleasing to the eye.
8	8.4354	1.9796	18. The lounge of my dorm is attractive.
9	8.5374	1.7449	19. The lighting in the corridors of my dorm is good.
76	8.6757	1.3259	20. The ceiling height of my room is adequate.
85	9.1622	1.5255	21. The inside of my dorm looks very pleasing.
28	9.3469	1.7582	22. Our recreational lounges provide a good place to relax.
34	9.6284	1.4347	23. In my dorm, I can arrange the furniture according to my personal ideas.
94	9.8176	1.2886	24. The size of my room is adequate.
54	10.2905	0.9494	25. In my dorm, I can choose my roommate.

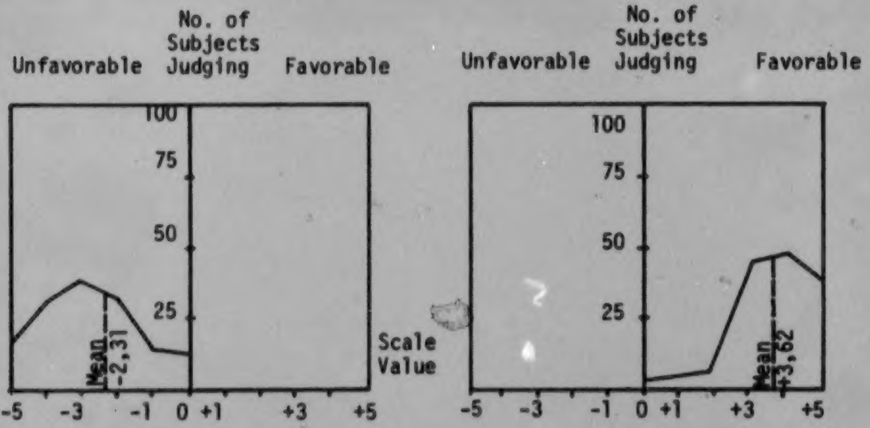
Figure 1

Combined Results of 5 Attitude Statement Ranking Sessions (N= 191): Frequency Distribution of Respondents' Judgments and Mean Value of Selected Statements



54. "In my dorm, I can choose my roommate."

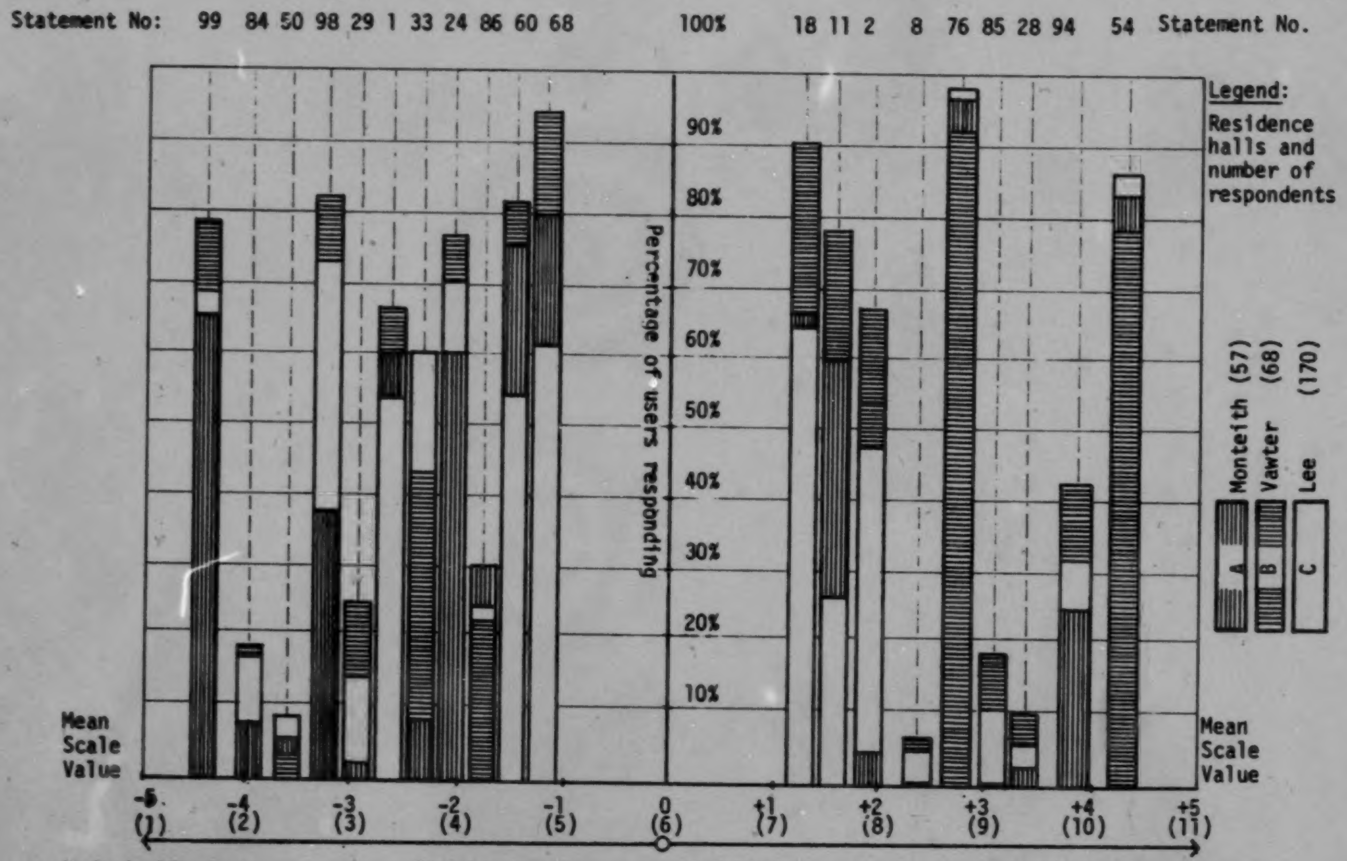
99. "There is no ventilation in my room."



33. "The floor material of my room looks very ugly."

34. "In my room I can arrange the furniture according to my personal ideas."

Figure 2: Comparative Profiles of Some Qualitative Judgments of Three Residence Halls



Undesirable features which did not apply to respective respondent's residence hall.

Statement numbers are located above each bar. For features contained in statements, refer to Table 1.

Desirable features which applied to the respective respondent's residence hall.

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Identification of Performance Criteria Using Multidimensional Scaling of User Evaluations

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The relative significance, accuracy and completeness of performance criteria for environmental control systems in buildings require testing through user evaluations in addition to customary laboratory research. Because of the inherent variability in human judgment, and the difficulty of interpreting direct quality estimations, such evaluations have not been widely used. Multidimensional scaling allows the reduction of comparative evaluations into a quantitative system of perceived environmental attributes. A questionnaire was used in evaluation of luminous environments as an example of the technique. Results provide for identification of perceived attributes and the scaling of the observed environments with respect to those subjective parameters so that physical measures may be related to human responses.

These methods differentially weight the salience of each attribute for each individual's judgment matrix, allowing access to data on individual differences that can assess the need for variety in a building system. The attribute structures may be applied to setting quality criteria across a wide range of environmental variables so that cost-benefit analysis may be done against overall performance rather than separate criteria.

La signification relative, l'exactitude et la plénitude des critères de performance pour les systèmes de contrôle du milieu doivent être mises à l'épreuve par les évaluations des usagers, en complément aux recherches habituelles de laboratoire. Du fait de la variabilité inhérente au jugement humain et de la difficulté d'interprétation des estimations directes, de telles évaluations n'ont pas été largement utilisées. L'échelle pluridimensionnelle permet la réduction des évaluations comparatives en un système d'attributs du milieu. On a utilisé un questionnaire pour évaluer des milieux éclairés et l'analyse des réponses a été traduite par un vecteur dans un espace pluridimensionnel. Les résultats permettant l'identification des attributs et des valeurs de l'échelle chaque stimulus de milieu, de sorte que des mesures physiques peuvent être reliées à des réponses subjectives.

Ces méthodes estiment différentiellement la projection de chaque attribut par rapport à la matrice de jugement de chaque individu, ce qui donne accès à des informations sur des différences individuelles qui peuvent coter le besoin de diversité dans un système de construction.

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Le système des attributs peut être appliqué en fixant les critères de qualité à l'égard d'une large série de variables du milieu de sorte que l'analyse coût/bénéfice se fasse en vertu d'étalons globaux plutôt qu'en vertu de minima et maxima locaux.

Key words: Color schemes; field studies; glare; illuminance; matrix analysis; multi-dimensional scaling; performance criteria; preference scaling; scaling; user evaluations; visual environment.

1. Introduction

User perceptions of environmental quality form the basis of performance criteria beyond immediate considerations of economy and safety. While laboratory testing can explore particular variables, the relative significance, accuracy, and completeness of performance criteria for environmental quality require testing using subjective responses to full scale functioning environments. Human judgment of quality is inherently variable, even where the questions asked are interpreted in the same manner, and where users share the same perceptions and preferences. New methods of analysis allow each person's data to be considered in the context of his other responses, and thereby take into account several interpretations of the same question, and different perceptions of the same environment.

The approach of comparing each person's response to his other responses allows existing environments to serve as a laboratory for the development of performance criteria. Humanly relevant variables are often qualitative, but in that responses can be shown to differ in a regular way to both qualitative and quantitative variation in the environment, these methods do not distinguish between two kinds of variables. It then becomes necessary to use external criteria to distinguish between aesthetic and more directly measurable variables, if indeed such a distinction is proper in considering the impact of the whole environment. Psychophysical research often exhibits a "quantitative bias" allowing only responses caused by stimulus variation to be considered relevant, irrespective of the breadth of human concerns. Dependence on such methods to produce overly restricted quantitative technical criteria can lead to buildings that are not as humanly acceptable, in the broader sense, as buildings designed by a sensitive individual. Such a situation reflects the inadequacy of the criteria in describing the full pattern of human needs.

Surveys of users have led to some information (1,2,3,4,5)[2], but compared to the laboratory studies on which standards are based, the results are ambiguous. Surveys are forced to rely on averages across both uncontrolled differences in individuals, and mixed interpretations of the questions. Even massive amounts of data result in high variances and mixed results which seem only to assess gross effects of environment.

2. Conceptual Model of Perceived Environmental Quality

The relevant perceived differences between sets of environments can be identified and structured as a system of attributes. The problem is to determine the number of attributes, their nature, and the way buildings may be designed to achieve different levels of performance with regard to these humanly defined aspects. An attribute may describe the quality of a color scheme, or the quantity of light in a room. The extent of these differences in quality or quantity may be modeled as distances between points on a line, where the points represent environments and the line represents one attribute. Several attributes may be needed to describe all views of the quality of a color scheme, and a person may subscribe to one or more of these views at one time in describing his perceptions. Different circumstances may emphasize different attributes as a function of mood, expectations, attitudes, and environmental function. Once the major attributes have been defined on the basis of subjective data, they may or may not relate to current technical performance criteria, and even where they do relate, their importance remains to be demonstrated relative to other qualitative perceptions.

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[2] Figures in brackets indicate the literature references at the end of this paper.

Definition of the attributes does not suggest their relative importance to an overall environmental quality that may be analyzed as a function of the perceived attributes. Any perceived attribute relevant to a particular environment should be considered in design -- but some are more important than others. Without trying to do justice to two decades of theoretical development, the system of preference models described by Carroll (6) may be used to structure the interpretation of overall quality. The simplest model suggests that preference increases along an attribute, and all that is needed are weights to describe the relative importance of each attribute. Alternately, moderation may be preferred, and it is necessary to define the preference peak or ideal point, and the relative weighting. The result of two attributes on which such peaks exist, such as temperature and light quantity, is a system of equal preference ellipses describing the trade-offs between the two attributes. Further complication allows rotation of these ellipses where subjects mix attributes, and have multiple peaks of preference. In general, given a set of overall preference ratings and a system of attributes, these models can be used in a regression analysis to find the significance of the attributes.

Given the system of preferences for individuals who are representative of building occupants, it is possible to consider an allocation of resources with respect to overall preference. The alternative may be to provide uneven levels of performance with respect to attributes, such as too much glare and surplus illuminance. User groups may be distinguished on the basis of perceptual style as indicated by their data, and designs can be formulated to allow an appropriate range of flexibility. Given the trade-offs, a variety of strategies may be considered to satisfy an overall performance criterion, rather than relying exclusively on isolated, and perhaps inappropriate, criteria.

Without such a method of developing criteria, benefits in cost-benefit analysis have been described only by fixed levels without information as to the effect of departing from these levels, while the cost determinations have become highly sophisticated. Trade-offs in equipment performance are acknowledged while human trade-offs remain unknown.

3. Scaling Attributes

Given the regression techniques for relating attributes to preferences, the problem is to find the attributes. Paired comparisons of stimulus similarity is a standard technique in multidimensional scaling (7), but Wish (8) and Osgood, Suci, and Tannenbaum (9) suggest obtaining a multidimensional response from each subject to each stimulus environment. The result is a stack of matrices or "solid" matrix as shown in Figure 1. An entry exists for each person's response to each rating scale for each of the M environments.

The analysis is based on the differences in each individual's ratings between different environments. On each scale, the differences in ratings between all pairs of environments (a matrix) are accumulated across individuals in a way that preserves the individually perceived attributes of the environments relative to that rating scale. The method was devised by Horan (10) and essentially makes the difference between two environments for any one scale equal to the root-mean-square of the differences in ratings by each individual. A possible matrix is shown in Figure 2 by a configuration of points that represent the environmental differences as distances. As shown in Figure 2, these distances may be adequately modeled by the use of two dimensions, although five environments could require as many as four dimensions. Where there is error in the original data, this error accumulates evenly between all pairs of points, while the less random perceived differences accumulate only on the axes representing perceived attributes. The additive error factor has been found to cause little harm in this analysis (11).

The configuration shown in Figure 2 has axes arbitrarily placed; any pair would reproduce the configuration. Attributes, however, cannot be arbitrary. Where questions overlap, either in interpretation of the question or in perception of the environment, it would be possible to find common parallel axes in the analysis of the matrices. These axes would differ in relative length but have the same configuration of points. This element of congruence offers information with which to locate the axes. Although developed in the context of analyzing somewhat different data, Carroll and Chang's procedure (12) of multi-matrix analysis may be used here. The set of difference matrices is approximated by a single matrix of stimulus coordinates, and a matrix of weights that shows how important each question is to each attribute (vector of coordinates). In general it has been found that only one orientation of the axes will best reproduce the original difference matrices.

By weighting each question relative to each attribute, several questions may relate to one attribute, or one question to several attributes. In this sense the attributes are independent of the questions and emerge despite differences in interpretation. The verbal interface, an inherently complex system, drops out since it is used only as a relative measure. The range of the questions does delimit the scope of responses, but even limiting the scope may result in more attributes than the M-1 possible dimensions for M environments can describe. In such cases it is necessary to analyze subgroups of questions, preserving interrelations between questions, but without mixing questions where attributes overlap due to co-occurance of relevant features through chance. Where individual rating scales require more analysis, the difference matrix between environments may be computed for each person, and these matrices analyzed together. Strong differences in individual weighting of attributes can allow correlated dimensions in a single rating scale to be separated. This is the approach used by Carroll and Chang (12), but it may be inefficient with many rating scales.

4. Example of Application

The visual environment of ten campus libraries was evaluated by 112 students using 10 questions to ascertain the performance of the libraries with respect to perceptual criteria, and the relation between these criteria and common indices of performance. The results yielded fourteen attributes including two related to the quality of the color schemes, two critical of glare from surfaces (desk surfaces and window surfaces at night), and others equally interpretable in physical terms, but described more fully elsewhere (13) and in Table I. Perhaps the relevant question in this regard is how well these procedures did in predicting what is already known, thus validating the method in the context of laboratory research while opening up less quantitative areas for further exploration.

Quantity of light was assessed on a seven point scale:

1 2 3 4 5 6 7
too little . . just right . . too much

and analyzed in four separate sub-groups of twenty-six individuals using separate matrices of inter-environment differences for each person. The four analyses each resulted in two dimensions. Corresponding dimensions achieved a product moment correlation with the appropriate common vector of between 0.91 and 0.98, indicating agreement among the separate analyses, and that two ways of viewing "quantity of light" are possible.

Stevens (14) proposed the formula $\psi = k(\phi-\phi_0)^N$, where ψ is the psychological response, ϕ is the stimulus magnitude with ϕ_0 as threshold, N is the characteristic exponent of the stimulus modality, and k is an arbitrary constant related to the stimulus units. For brightness, an exponent of 0.33 was found by Stevens through exhaustive laboratory tests. In Figure 3, both the average quantity ratings and the average measured footcandles, according to the IES (New York) procedure (15), are plotted against the subjective scaled magnitudes of one of the two quantity attributes. From this data (i.e., $\phi = 430$ lux or 40 footcandles at $\psi = 4.0$) the exponent is 0.347, showing the partial, but not unique, validity of illuminance as a measure of light quantity, and log (illuminance) as a proper indication of subjective quantitative differences in illuminance. As can be seen from the figure, all but three environments were rated within 5% of the illuminance. This can hardly be called subjective error; on the contrary, while illuminance fits well, it is not entirely the correct measure. This may be termed "objective error" since such measures are often called objective.

Subjective illumination is only one attribute related to "quantity of light." The other is less easily described, but appears to relate to the overall room luminance. Figure 4 compares the two attributes and shows general agreement between the two, except for three environments. One, RR, has much lower room luminance since the main fixtures are mounted only 45 cm. (18 inches) above the tables, although the table illumination is 690 lux (64 fc). Above these fixtures only 30 lux (3 fc) is provided making a very dim space. The two environments with highest disproportionate room luminances had light colored walls (SS, 73%), or uniformly colored surfaces (MR, all medium brown). With few examples, conclusions cannot be drawn, except that illuminance is not an entirely adequate measure. Lynes (16) came to similar conclusions, but his measure (scalar illumination) did not predict the second attribute.

From this result it can be seen that the rough ratings by individuals in different environments can be analyzed to yield information comparable to well known laboratory work. The resulting attribute scales, when compared back to the original mean ratings, approach a "ratio" level of measurement where the percent differences between ratings related to single attributes are significant. Since the same methods were used to scale the quality of the color scheme, these attributes are also perhaps on a ratio scale.

Perhaps the most surprising result of the scaling was the rating of 430 lux (40 fc) as "just right," not too much or too little. While the scaling was done at night with walks between environments, sufficient time was allowed for light adaptation. Lighting engineers often install much more than this level. While illumination preferences are rarely investigated these days, older data show similar results: 410 lux (38 fc) (17); 540 lux (50 fc) (18); 560 lux (52 fc) (19). If increased visual capacity with illumination (20) is applicable to ordinary reading at these levels, then the preferred illuminance may be a trade-off with glare. Figure 5 shows the attribute related to glare plotted against the subjective illumination (on arbitrary scales). The relationship seems quite regular, although it is possible to do better with respect to glare (B, a high luminous ceiling), and also worse (H, spotlights giving 17000 cd m^{-2} (5000 foot Lamberts) at 45 degrees) than the general relationship suggests. The very worst environment (MT) raises questions about the definition of glare, as the maximum luminance of the fixtures is only 3100 cd m^{-2} (900 fL) at 45 degrees, but the fixtures are arranged in a striking grid pattern that is a possible source of adverse reaction. As glare formulae are computed for the worst case (13), it is worth noting that multidimensional scaling integrates the impression of the room across all the seating positions occupied by the respondents, and in general it produces indices applicable to the unit of analysis, the room.

5. Implications

Performance criteria for buildings have been based on indirect measures of environmental quality found through parametric investigation under conditions of isolation from normal environments. These results indicate that full scale environments can yield equally good parametric data, while including the qualitative aspects that affect human perceptions of environmental quality. The attributes defined are natural parameters of environment quality from which performance may be developed, with criteria based primarily on human response and not on ease of measurement or even direct measurability. The best measure of man's environment is man himself, and perhaps now the performance criteria can reflect more of the full spectrum of human needs in the environment.

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TABLE I: ATTRIBUTES FOUND

Attribute (rating scales)	Interpretation	Implication
Room Illuminance (quantity of light)[a]	Log (illuminance) is directly related to a subjective response; there is a definite preference level.	Preferences exist and may be found for use in design, effectively integrating all visual concerns on a subjective level.
Room Luminance (quantity of light)	Relates to illuminance but modified by wall reflectance to exceed or lag perceived illuminance	Two measures are needed to specify subjective quantity, only one rating scale is needed for the method to uncover this fact.
General Glare (glare from lights)	Relates to perceived illuminance, but may be much better or worse depending on fixtures; it appears to relate to general room view.	Simpler than glare formulae, exceptions easily understood, high luminous ceilings (good), small bright lights (poor), strong dense patterns (poor).
Fixture Glare (glare from lights)	Similar to general glare except small fixtures even worse; indistinct edges on luminous areas are also poor.	Glare is also two dimensional requiring two predictive procedures which may be intuitive or at least simpler than current formulae.
Evenness of Illuminance (distribution of light, fixture type, fixture arrangement).	Related to the log of the percent deviation from the mean illuminance over a range of 10% to 75%. 33% seen as average and is the standard criterion.	Evenness of illumination may be assessed by untrained subjective observers; down to +5% variation absolute level of 'average' relates to existing criteria.
Color of Light (color of light)	Warm white good, mixed warm and cool less good, cool white poor, mercury vapor very poor.	Color of light is perceived and may be evaluated, should help set adequate standards which are apparently needed.
Glare from Desks (surface glare)	Specular surface reflections on desks seen as undesirable.	This problem can be avoided; some process is necessary to accomplish this avoidance in design.
Glare from Windows at Night (surface glare, glare from lights).	Reflections of lights in windows seen as undesirable, window coverings prevented problem.	Again avoidable; mixture of rating scales shows ambiguity of verbal interface and ability of method to deal with it.
Surface Colorfulness (color of surfaces).	Graded from 'colorful' to very poor color selections, brightly colored surfaces appreciated, also wood surfaces.	Does not resemble results from color chip on background evaluations, perhaps more relevant.
Surface Color Naturalness (color of surfaces).	Graded from rich natural colors to 'plastic' colorfulness, wood appreciated with uneven grain.	Again no simple precedent, seen by a different population than 'colorfulness' attribute.

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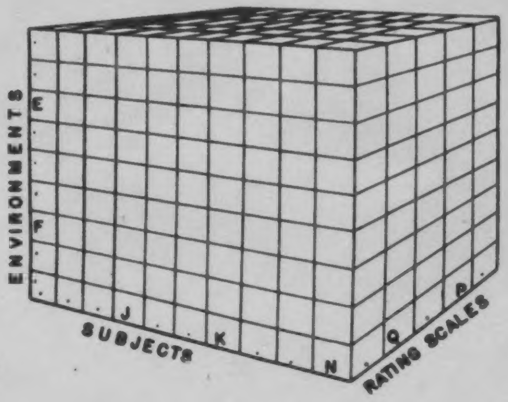
[a] Quantity was rated: 1(too little), 4(just right), 7(too much). All others were rated: 1(poor), 4(average), 7(good).

Table I (cont.)

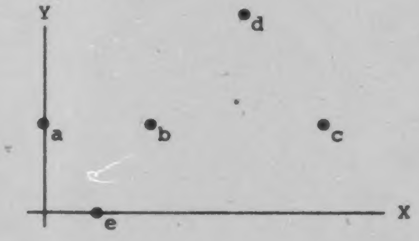
Attribute (rating scale)	Interpretation	Implication
Fixture Arrangement (fixture arrangement)	'Gestalt' principle, clear, simple organizing pattern, luminous ceiling or grid best, rectilinear next, many small sources poor.	Grid relates to glare (strong dense pattern), yet appreciated for organization; interesting.
Fixture Type (fixture type)	Rectilinear fixtures preferred, or high luminous ceiling; low luminous ceiling not preferred nor small or symmetric fixtures.	Could there be qualitative fixture type criteria related to perceived quality?
Modeling (modeling)	Luminous ceiling and spot down lights rated low, rectilinear fixture arrangements did well.	Even in this country (USA) modeling is perceived, but not the need for engineering criteria.
Overall Evaluation (general impressions).	A catch-all dimension, seems to relate to most other attributes but no statistical test possible with so many predictors.	More environments need to be evaluated to learn trade-offs.



$$D^{P}_{EF} = \sqrt{\sum_{J=1}^{J=N} (X_{EJP} - X_{FJP})^{2}}$$

Figure 1: Data solid or stack of matrices and formula for computing the difference between two environments (E,F) for a single rating scale (P) across the subjects (J, J=1, N).

Figure 2: A representative difference matrix and associated spatial configuration along with the representation of it as projections on arbitrary axes (X,Y) of a dimensions matrix.



	a	b	c	d	e
a	0	2.0	5.0	4.4	2.0
b	2.0	0	3.0	3.0	2.0
c	5.0	3.0	0	3.0	4.4
d	4.4	3.0	3.0	0	5.0
e	2.0	2.0	4.4	5.0	0

Difference Matrix

X	0.0	2.0	5.0	3.5	1.0
Y	1.7	1.7	1.7	4.3	0.0

Dimensions Matrix

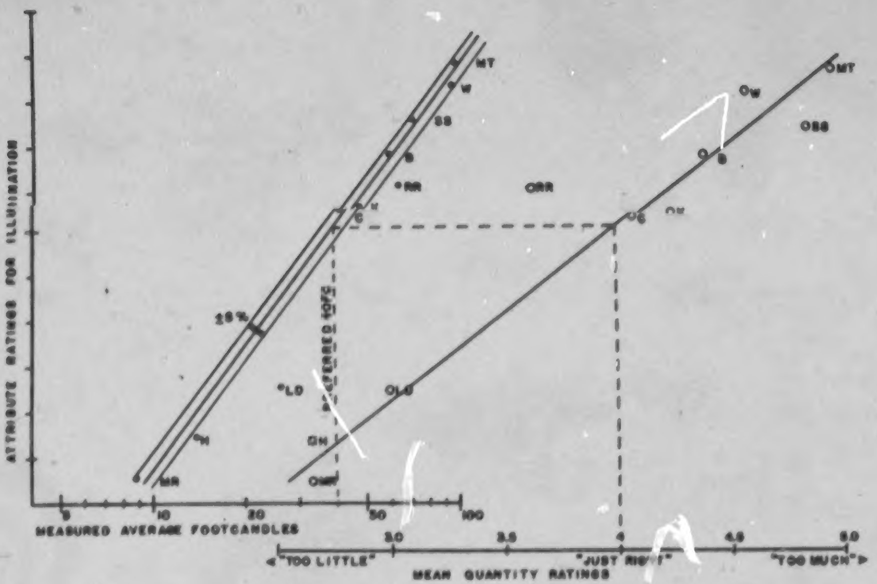


Figure 3: The subjective illuminance attribute scale compared to both the illuminance measure and the mean quantity ratings. The relation between the mean levels and mean assessments taken though the attribute scale approximates a ratio scale of subjective response.

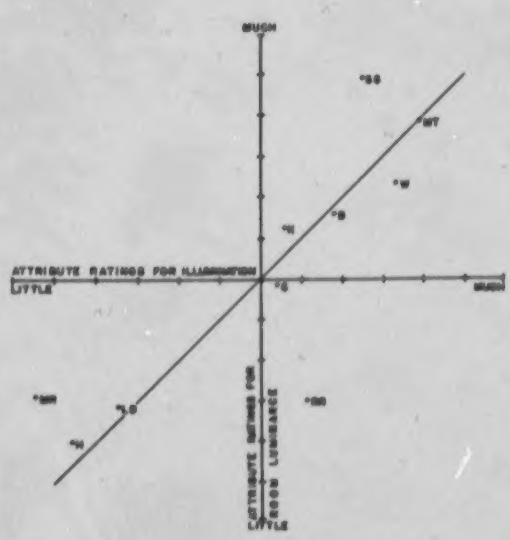


Figure 4:
Comparison of the two kinds of subjective assessments of light quantity illustrating the general similarity and environments where the assessments using a single question differed.

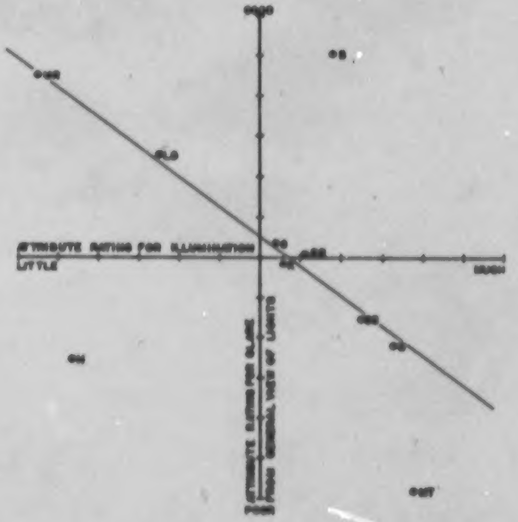


Figure 5:
Comparison of the subjective assessments of "general view" glare to the perceived illuminance. Although generally related, there are exceptions.

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Performance: the New Language of Design

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With the scattered development of tools for user needs analysis, the measurement and specification of performance, product analysis, and building evaluation, there is a growing need for unification of these concepts into a single framework. A definition of the performance concept is presented which mediates between the measurement of benefit and the costs of design solutions. With performance as a mediating concept, we are able to formulate user needs as the correlation between performance and benefit, and to analyze products in terms of the relationship between their cost and their performance. The Performance/Benefit correlation (user need) is a user characteristic independent of product Cost; while the Cost/Performance relationship is a product characteristic independent of Benefit to the user. This paper clarifies the relationship between this definition of the performance concept and various forms of analysis, design, and evaluation common to the design of buildings. It further explores possible shifts in the practice of design as skills become more specialized in the building industry.

Un besoin croissant se fait sentir de réunir en un cadre unique les moyens développés de façon dispersée par l'analyse des besoins de l'usager: les mesures et spécifications de la performance, l'analyse du produit et l'évaluation de la construction. On présente une définition de la notion de performance qui sert d'intermédiaire entre l'estimation du bénéfice et le coût des solutions adopteés par le projet. Avec la performance prise comme concept intermédiaire, nous pouvons formuler les besoins de l'usager comme la corrélation entre la performance et le bénéfice, et de même nous pouvons analyser les produits en fonction du rapport entre leur coût et leur performance. La corrélation Performance/Bénéfice (besoin de l'usager) est une caractéristique de l'usager indépendante du coût du produit, tandis que le rapport Coût/Performance est une caractéristique du produit indépendante du profit de léusager. Cette communication clarifie le rapport entre la définition de la notion de performance et des formes variées d'analyse, de calcul et d'évaluation qui relèvent des projects. Elle explore aussi des changements éventuels dans l'étude des projets à mesure que les compétences deviennent plus spécialisées dans l'industrie de la construction.

Key words: Cost; design; industrialization; performance; user needs; value system.

1. Introduction

The design of buildings is the optimization of resources in the creation of a functioning human environment. Traditionally, the designer weighed cost against benefit to determine the best design solution. Benefit was determined through direct experience with alternative solutions. The designer knew that one particular wall construction provided privacy between bedrooms, while another did not. There was no need for a measurement of acoustical separation, since it was the direct human experience of privacy and not the physical property of acoustical separation that the designer was after.

Thus, the designer's knowledge has been based on his experience of the direct correlation between design solutions and human need.

But this formulation of design knowledge has its shortcomings. For example, building codes which express the need for safety in terms of specific design solutions are rapidly outdated by changing technology. Reformulation of codes in terms of building performance renders the code independent of particular design solutions; new solutions must simply meet the required levels of performance.

The concept of building performance is having a radical impact on the formulation of the designer's knowledge of human needs, and of alternative design solutions. This reformulation is causing a realignment of design skills which will ultimately result in reorganization of the design professions.

This paper is an attempt to clarify the relationship between the performance concept, the new formulation of design knowledge, and the realignment of design skills.

2. The Changing Context of Design

There are two revolutionary forces which are changing the context of building design. First, industrialization is quickening the pace at which new methods, new materials and new skills flood the marketplace. We are passing from a time when buildings were built by widely used methods to a time when most building will be produced by manufacturers, each of whom has his own production technology. This proliferation of building methods severely threatens the designer's ability to know alternative building methods and their costs.

Second, the western world is beginning to emerge from the period in which goods are mass-produced for a faceless marketplace. There is a growing consciousness of individual differences [1][1]; people want to participate in the decisions which shape their environment. Mass education, mass housing, mass consumption do not meet the need for individual prerogative.

Just as this new consciousness is emerging, new technology is emerging in response, largely facilitated by the development of computer science. Post-industrial technology will be capable of mass production with variety (which, in the industrial age, were presumed to be mutually exclusive).

Not only will the consciousness of the differences between individuals directly affect the design of buildings, but the accelerating changes in the way we confront other human problems will be reflected in building design. For instance, the design of schools has recently reflected not simply new methods in education but the likelihood of future changes. Schools must be susceptible to continuous reshaping in response to these new methods.

In housing, the ideal of a good home for every American cannot be answered by one ideal solution. Not only are people different in age, race, culture and economic status, but their life styles differ, and these differences are likely to become more drastic in the future.[2]

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[1] Figures in brackets indicate the literature references at end of this paper.

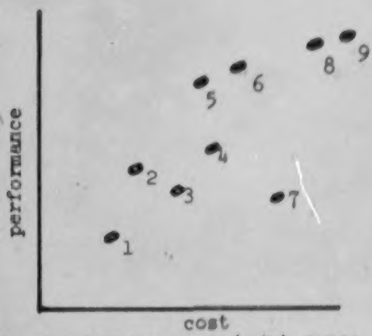
The designer can no longer afford to assume an identity between his own value system and that of the user of the building he is designing. Each new design effort will involve substantial analysis of the values and priorities of the user. That which served the designer of the industrial age as a stable body of knowledge about the human use of buildings will no longer suffice.

So, the traditional knowledge and skills of the designer are severely threatened. What could traditionally be accepted as a "good" design solution can now be invalidated overnight by new technological development, or by the changing values and priorities of the building's user.

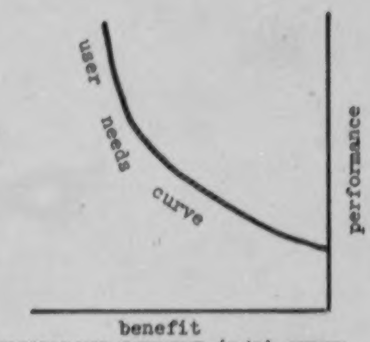
3. The Performance Concept

The concept of building performance allows us to reformulate our knowledge of the resources from which the building is assembled and the value system of the building's user.

Our knowledge of building resources and alternative building solutions can be formulated in terms of the ratio between their cost and their performance.[2] The cost and performance of comparable products can be graphed as shown below, left. This cost/performance (C/P) ratio allows us to characterize alternative building products independent of the value system of a particular user.



COST/PERFORMANCE (C/P) RATIO



PERFORMANCE BENEFIT (P/B) CURVE

Our knowledge of human needs can be formulated in terms of the relationship between performance and benefit. Performance is a measure of physical attributes of buildings, such as sound reduction in walls. Benefit is a measure of gain, either human well being, such as privacy, or financial gain, such as profits from a well organized factory. User needs are the correlation between performance and benefit. A user need expresses that particular levels of performance correspond to particular levels of benefit, as shown above, right. This relationship is a user characteristic and is independent of the availability of resources to provide the performance.

Although the C/P and P/B ratios are not precise analytical tools, certain generalizations can be made about their shapes and their relationships to one another.

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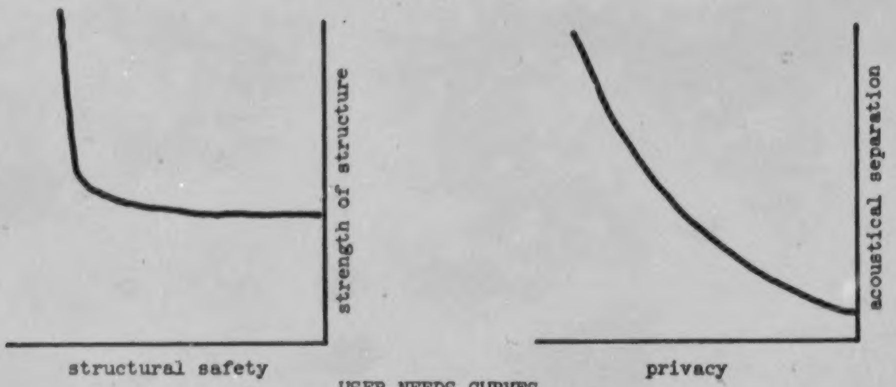
[2] Throughout this paper, products are dealt with as though they have one measure of performance. Although this is seldom the case in practice, the simplification serves the purpose of the paper, to show the interrelationships between measures of cost, performance and benefit. The model may be extended to deal with multiple measures of performance by adding dimensions perpendicular to the performance scale. Although the development of the model in such a manner would be essential in developing a workable analytical tool, it is beyond the scope of this paper.

4. User Needs (Performance/Benefit)

The human need for environment consists of a hierarchy of needs, each of which relates building performance to benefit. In analyzing user needs, we break down this hierarchy in order to arrive at a level of detail where building performance can be measured. For instance, the need for safety breaks down into structural safety, fire safety, biological safety, safety from accidents, and so forth. Fire safety is further composed of life safety and protection of property.

The relative importance of these needs is a function of individual priorities. Some people value privacy higher than view, while others would prefer the view. Psychological and cultural needs tend to vary from person to person, while biological and physiological needs tend to be shared. The priorities among needs is reflected in the user needs curves by the measure of benefit to the user.

Several observations can be made about the curves themselves. First, each curve tends to cross the performance axis at a point of positive value. This simply means that there is a threshold level below which performance is of no benefit to the user. We can further generalize that at the outer end of the P/B curve, it will tend to become vertical. There is a limit beyond which increased performance yields no additional benefit.



USER NEEDS CURVES

The two needs curves shown above both illustrate these two generalizations about what happens at the ends of the curves. Their difference in shape, however, illustrates the two basic types of needs curves.

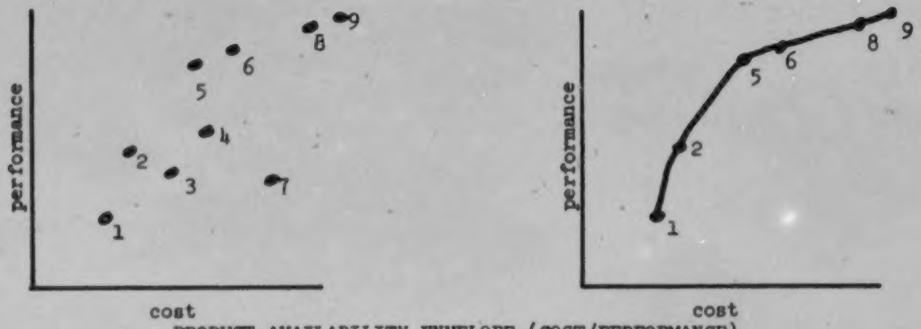
Structural safety is an example of an inflexible need. Structural performance below a certain point yields no benefit and above that point additional performance results in little additional benefit. Once an inflexible needs curve is established, designers can easily agree on the appropriate level of performance, the point at which the curve turns (the breakpoint). In the example, this would be the point agreed upon as structurally safe.

Privacy is an example of a flexible user need. There is no one breakpoint at which additional performance gives no additional benefit. With such a need there can be no agreement as to the total appropriate level of performance based only on the user needs information. A flexible curve does not mean that the individual does not care what level of performance he is getting. Quite to the contrary, the curve indicates that additional levels of performance will buy additional privacy.

5. Product Availability (Cost/Performance)

The C/P graph below shows the cost and performance of several comparable products. The distribution of these products forms a boundary in the upper left direction, as shown in the graph on the right. The nearer a product is to this boundary, the more competitive it is. This boundary is called the product availability envelope.

Product availability has the characteristic of diminishing returns, just as user needs do. As more and more resources are spent on a product, each additional expenditure results in smaller increases in the performance level.



PRODUCT AVAILABILITY ENVELOPE (COST/PERFORMANCE)

Although there are only six points on the curve that actually represent products, the envelope represents the theoretical existence of a continuous spectrum of products.

Traditionally, manufacturers have offered a series of models of a product giving a range of price and performance. In the future, manufacturers will be able to analytically determine the full spectrum of products which comprise the product availability envelope. Advances in production techniques will enable the manufacturer to produce whichever "model" suits the priorities of the user. Work has already begun in this direction. Owens-Corning Fiberglas Corporation has made the following proposal: "... to develop a basic computer-assisted system for selecting and optimizing combinations of surface and core materials for exterior non-load bearing housing unit wall panels to yield maximum cost/performance."[2]

With the introduction of measures of performance as an intermediary between cost and benefit, we create two independent bodies of knowledge which become the analytical basis for design decisions. This new form of knowledge will produce profound and timely changes in the practice of design.

Segregation of design knowledge into two independent bodies has two extraordinary advantages over the traditional direct correlation between cost and benefit. First, the knowledge characterizes only one set of variables, either user needs or available resources, and thereby has far greater permanence than knowledge which varies with both.

User needs data, which correlates performance levels with benefits, fluctuates only with changes in the value system of the user. It is unaffected by fluctuations in the availability of resources. Resource data is likewise unaffected by fluctuations in the priorities of users.

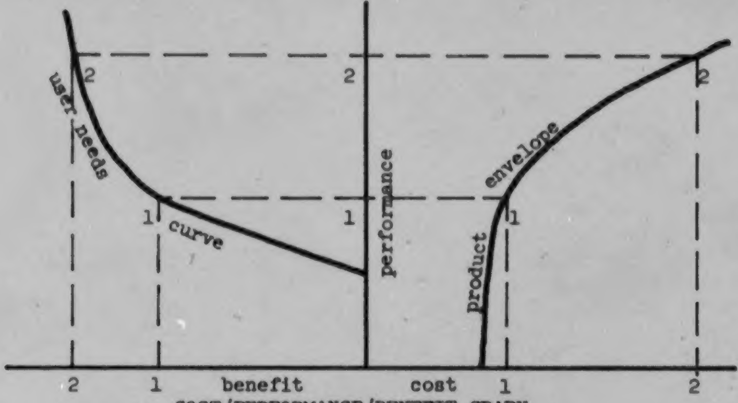
Second, the independence of these bodies of knowledge from one another suggests the development of specialized skills. There are signs that this is already taking place. These trends will be discussed more fully below.

6. Design and the Performance Concept

Having sketched out the formulation of knowledge which is made possible through the use of the performance concept, we are now ready to examine design in light of this new form of knowledge.

So far, the analyses of user needs and of product availability have been considered separately. The graph below shows the juxtaposition of the user needs curve for a single performance characteristic against the availability envelope for products which supply that performance characteristic. On the graph, the correspondence between the benefit scale and the cost scale has been traced through for two values. Benefit 1 is derived from performance level 1, which is provided by product 1 which has cost 1. The cost of any benefit can be traced through in a like manner. The performance characteristic is a common measure which allows the translation of costs into benefits.

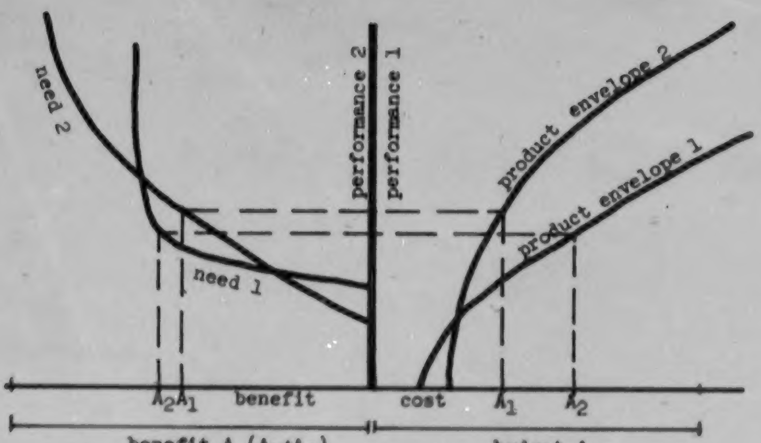
Design is a decision-making process which allocates resources to those levels of performance which will deliver the greatest overall benefit.



COST/PERFORMANCE/BENEFIT GRAPH

Design problems present us with a complex hierarchy of needs and a complex hierarchy of products from which potential design solutions can be assembled. However, the basic concept of the design decision can be demonstrated through the use of two simple examples.

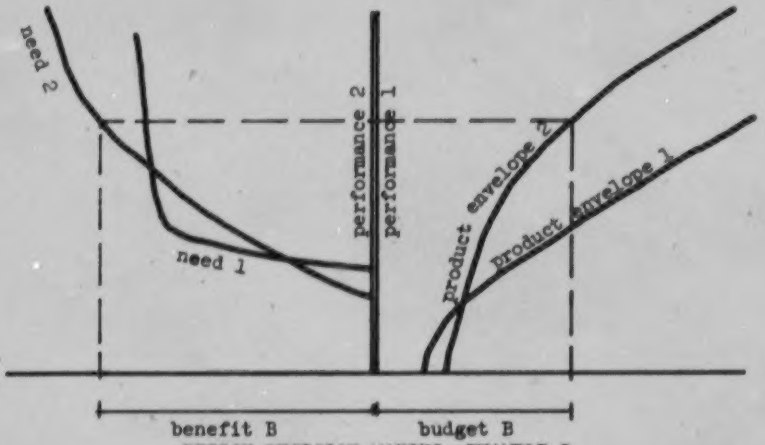
The designer is asked to allocate a fixed budget to the satisfaction of two user needs. The design objective is to maximize the total benefit gained from the products selected. The user needs curves and the product availability envelopes are presented below for the two performance characteristics needed.


need 2
need 1
performance 2
performance 1
product envelope 2
product envelope 1
A_2
A_1
benefit
cost
A_1
A_2
benefit A (A_1+A_2)
budget A

DESIGN DECISION-MAKING: EXAMPLE A

In the first example, budget A is allocated to the problem. We first trace through the benefits which will accrue from allocation of the total budget to either need 1 or need 2. Need 2 yields the greatest benefit. The second step is to remove increments of budget from need 2 and, applying them to need 1, determine if the benefits gained from need 1 compensate for the reduction in benefits from need 2. Initial reductions in the amount allocated to need 2 are more than compensated for by the benefits gained from need 1. This continues to be so until we increase the budget of need 1 to a point where we reach the breakpoint in needs curve 1. At that point, a further shift in budget from need 2 to need 1 loses more benefit than it gains. The combined benefit from needs 1 and 2 at this optimum allocation point is shown below the benefit scale.

With a reduced budget, shown as budget B below, the same procedure as used above shows that at no point is the reduction in benefit from need 2 compensated for by the benefit from need 1. Thus, budget B is most effectively allocated entirely to the satisfaction of user need 2.


need 2
need 1
performance 2
performance 1
product envelope 2
product envelope 1
benefit B
budget B

DESIGN DECISION-MAKING: EXAMPLE B

These simple examples demonstrate the sort of decisions which have always taken place in design; they do not present new patterns of decision-making; they reformulate design decisions in terms of the performance concept and our new form of design knowledge, the user needs curve (Performance/Benefit) and the product availability envelope (Cost/Performance).

The purpose of this discussion is not to present an analytical method ready for application to complex design problems. The purpose is to show the interrelationships between design decision-making and the knowledge of user needs and product availability on which it is based. Any decision which fixes the level of a performance characteristic is a design decision. It synthesizes a knowledge of user needs and product availability. Appropriate levels of performance cannot generally be determined working only from user needs or product availability, although the more inflexible the user needs curve, the more we can agree on a level of performance without reference to cost. However, it has become common practice in the development of performance standards to select the "right" level of performance without consideration of product availability. Such standards as the Operation Breakthrough Guide Criteria [3] have this property of specifying building performance without allowing design tradeoffs in each individual design situation.

7. Evaluation

Buildings designed through the use of the performance concept should be evaluated in two ways. Product evaluation measures the performance of the building against the performance levels and costs predicted. This evaluation serves both to rectify any shortcomings in the building's construction and to provide feedback which verifies and updates the designer's knowledge of product availability.

User needs evaluation measures actual user satisfaction with the levels of performance provided. This information feeds back to the user needs assumptions on which the design was based.

8. Realignment of Design Skills

The building designer is overwhelmed by two trends which are outside of his control: increasing consciousness of individual differences and an explosion in the development of new building technologies. Both of these trends increase the potential for well designed environment while decreasing the traditional designer's ability to design them. In reaction to these trends, a realignment in design skills is taking place. A number of examples of this realignment are listed below.

8.1 Design by Manufacturer

With the gradual industrialization of building construction, manufacturers are responsible for design decisions of larger and larger scale. These decisions must be made by the manufacturer, because only he has the information regarding the cost of production of various design options. Although they are currently in the minority, some manufacturers are recognizing that their decisions on what to produce must relate to the individual priorities of the products user. For example, in housing, Pantek Corp. has proposed to develop a computer-aided system for designing individual houses working with the prospective occupant.[4] In order to meet individual needs with a mass-produced technology, these manufacturers have designed assembly systems which allow construction of a variety of product configurations from a limited range of standardized parts.

8.2 School Systems

In the school construction industry, industrialization has reached the scale of building component, and production is far more capital-intensive than in the housing industry. In his school project built from components, the architect is able to concentrate more effort on analysis of user needs and selection of components, since decisions regarding the detailed design of the components are made for him by the manufacturer.

8.3 User Needs Research

There is a substantial increase in the amount of research into the relationship between people and their physical environment. As a result, there is a growing number of specialists in the field of user needs. The function of these specialists is to develop the body of knowledge which relates human benefit to environmental performance. But this is where their function stops. Without knowledge of the costs of solving these problems, the user needs specialist cannot synthesize his analysis into design decisions. He cannot fix the "best" level of performance.

8.4 Turnkey Procurement

The increased use of turnkey procurement methods by public housing authorities, the military and other housing sponsors, represents another shift in design practice. The turnkey approach provides an insight into design practice of the future. Prior to procurement, the sponsor does a thorough analysis of user needs. The user needs statements become the basis for evaluating proposed design solutions.

Prior to responding to such a user needs statement, the proposer, perhaps a manufacturer, must have a thorough knowledge of the cost/performance functions for the range of design solutions which he is capable of producing. The wider this range of solutions, the more likely the proposer will be responsive to the specific needs of the problem at hand.

When presented with the request for proposals, the manufacturer then designs the solution which most effectively applies the resources at his disposal to the problem.

9. Conclusion

As the industrialization of building increases, the building designer either will align himself with the user as the selector of building technology, where his generalizations and preconceptions will have to give way to analysis of individual needs; or he will align himself with the producer, where the traditional detachment from a vested interest in building construction will give way to advocacy of a particular technology. The potential for good building under such an advocacy system is great, but there will be a painful realignment of design skills.

This new specialization in design will require far more effective communication between participants than we have today, communication which will only be possible if designers have a common language which bridges their specialized concerns with Cost and Benefit. Performance will become this new language of design.

10. References

[1] Toffler, Alvin, Future Shock, Random House (1970)

[2] Owens-Corning Fiberglas Corporation, Operation Breakthrough Proposal for Optimization of Wall Cross-Sections for Modular Wall Panel Systems (1969)

[3] Department of Housing and Urban Development, Guide Criteria for the Design and Evaluation of Operation Breakthrough (1970)

[4] Pantek Corporation, Preferred Type B Proposal for Development of a Computer Aided Design, Estimating and Scheduling System (1970)

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

Consideration of Externalities to the Basic Performance/Cost Evaluation of Buildings in the Design Process

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Starting from (1) an adequate analysis of buildings into subsystems and their functional elements
(2) the statement of required technological performance for each element of a proposed building and
(3) the budget cost for each element of a proposed building, the question arises - what else should the designer include in his evaluation of each building element to maximize overall User Satisfaction?

These externalities to the basic technological performance and cost of each element are described and discussed and their relationship to each other exposed on a Value Axis. They comprise a range of factors from Hypothetical Minimum Cost to User Values. They are interrelated and influenced by the Project Roles which are responsible for each section of the Value Axis on each Project. Such externalities play an important part in the integration of the elements to create a desirable overall project and the designer should direct his attention to them to achieve optimum overall balance between Performance and Cost.

The conclusion reached is that while the above ratio of technological performance to cost of each element is a desirable starting point for building evaluation, the externalities on the Value Axis also play a considerable part in selecting the building materials which can provide maximum building User Satisfaction.

A partir (1) d'un bâtiment et d'une analyse convenable ses sous-systèmes et de leurs éléments fonctionnels,
(2) des performances requises et
(3) du budget pour chaque élément du bâtiment projeté, on se demande quels autres facteurs le projecteur devrait inclure dans son évaluation de chacun des éléments dans le but de maximiser la satisfaction globale de l'usager.

Ces facteurs externes à'la performance et au coût de chaque élément sont décrits et commentés et les relations entre ces facteurs son presentées sur une échelle de valeurs. Ils constituent un spectre allant de l'hypothètique moindre coût jusqu' aux valeurs de l'usager. Ils sont reliés et influencés par des rôles du projet affectant chaque section de l'échelle des valeurs.

Ces facteurs externes sont importants lors de l'intégration des éléments dans le but de créer un projet complet souhaitable et le projecteur devrait leur prêter attention pour obtenir un équilibre global optimal entre la performance et le coût.

On conclut que bien que le rapport de la performance au coût de chaque élément soit un point de départ souhaitable, les facteurs externes de l'échelle des valeurs peuvent aussi avoir une influence considérable lors de la sélection des matériaux pour maximiser la satisfaction de l'usager du bâtiment.

Key words: Building; competitive market; construction; cost; evaluation; materials; performance; price; user; value.

Introduction

The evaluation of performance of materials and components of buildings is at its most crucial for a building in the design process. It is there that the building is crystallized for its whole life. After design, the budget costs become virtually sunk costs and the performance becomes that of a fixed asset - difficult and costly to adjust.

In the evaluation of complex products e.g.,buildings, against certain criteria, the usual mode of operation is to analyze the complex product into its subsystems and perhaps even into differing functional elements of these subsystems. Then the subsystem in total, e.g.,a complete floor system, or an element thereof, such as floor covering, is evaluated against the required criteria. This process is then repeated for all subsystems and elements thereof, providing an evaluation of the whole complex product against the desired criteria.

As there are many ways of analyzing buildings into subsystems and elements, let us assume that a suitable one exists and that the basic evaluation of each element is to be carried out against the criteria of (1) Performance i.e.,technological performance and (2) Cost i.e.,life cycle cost.

The required technological performance of each element will be derived originally from the stated Users Needs for the building and translated into technological performance for the subsystem and then to the required technological performance of the elements within that subsystem.

The required budget cost for an element will be derived from the total project budget via the subsystems budget. The origin of the project budget will be the designer's cost data bank of past projects updated and structured for the type of project under consideration. The designer now has at hand:

(1) the technolgical performance required of the element and
(2) the appropriate budget for that element within the context of the whole project.

Thus the designer has a Performance/Cost datum for the element and must search for appropriate materials and components, which will provide at least that Performance/Cost datum.

Without precluding the potential for trade-off decisions at subsystem level for example, in this paper attention will be directed at evaluating and relating the performance and cost of one element to the whole project at the time of design. This will involve the consideration of externalities.

Externalities are defined as aspects of, or influences upon the design decisions for each element which are beyond its specific technological performance and life cycle cost. They are concerned with the provision of the best overall performance and cost for the building project as distinct from the simple but naive summation of the performances and costs of all elements of the project.

Let us consider that the designer has a number of alternatives to fulfill the Performance/Cost datum for an element of the building and now must further evaluate each before making his final decision. What should he consider other than technological performance and life cycle cost of each element?

Because buildings are made up of many small pieces i.e.,elements, the correlation between these pieces and
(a) one all embracing construction process
(b) the required and various specialized roles in the construction project team
(c) nonbuilding influences on the project, e.g. the effect of land prices on the size of the building and its constituent materials and
(d) the building being only the physical vessel which carries the services required by the user, e.g. privacy, warmth etc.,
can be considered as externalities impinging on the design choice of each element of the building and their basic technological performance and cost.

The Value Axis - Description and Discussion of its Factors

The Value Axis comprises a linear scale, upon which are positioned the various value factors of a building project. In ascending order of positive dollar size, these value factors are Hypothetical Minimum Cost, Project Cost, Project Price, Rental Price and User Value.

Hypothetical Minimum Cost is the minimum cost of the materials e.g., bricks and the construction resources e.g., men and machines necessary to build the project i.e., with neither wastage of materials nor redundancy in the construction processes.

Project cost is the actual cost of materials and construction resources necessary to build the project, i.e., it includes the material wastage and construction process redundancy in labor and plant etc.

Project Price (Present Value) is the present value price of the whole project and comprises the capital price of the building, the capital price of prerequisites e.g., land, and the present value of the functioning cost of the whole project over its life span. Each of these will include the profits of their executant roles.

Rental Price (Present Value) is the capitalized present value of the rental price charged in the open market place for the use of the whole project and may be the rental price datum for that type of project in that general location for that time.

User Value is the capitalized present value placed upon the use of the project by the user i.e.,it will be derived from the user's perception of the project. It is clear that the value placed upon the project will vary from one prospective user to another and to some it may be less than the rental price. This User Value will encompass the whole project and include economic, social and psychological advantages to each potential user, e.g., location in relation to other buildings and functions and also the psychological and aesthetic-image aspects of the building.

Attempts have been made by producers to analyze products and place a value upon the features of the products which are desired by the open market purchaser, but these processes are extremely complex even with simple mass manufactured products. Even such rational value analyses are still influenced by the location and time variations of the state of the market. The issue is compounded for complex products such as buildings. These aspects of the abstract product surround,to the whole of the Objective Product (i.e.,the building),will directly influence at least the Rental Price and User Value Factors of that Objective Product. This changes the upper sections of the value analysis from simple cost accumulation to a market place valuation of the end product in use.

Construction Inefficiency is the wastage and redundancy in the construction process. It is a result of (1) the lack of consideration of the erection process in the design of the building and (2) the actual redundancy and inefficiency of the erection process itself.

The former must be minimized only to the extent that it does not infringe unfavorably on the in-use Functioning of the Building during its Life Cycle. Dimensional and Modular Coordination are preeminent among the tools which can achieve this goal.

The latter can be minimized by clearly transmitting the envisaged best-erection process for that building to the various executants of the construction roles i.e., subcontractors and suppliers and especially to the management contractors who coordinate their work.

It is advantageous for the designer to conceptualize the User Value section of the Value Axis in two segments. These are:

a. Competition Neutralization, the lower segment, which will be directed at ensuring that the building being designed, contains all the features or their equivalent, which are present in the performance of buildings against which it will compete for renters and

b. Competitive Advantage, the upper segment, which will be directed at including in the designs features which not only adequately satisfy user needs but do so in a manner which provides uniqueness to the building. It is these upper segment features which will occupy the focus of the marketing of the building and provide its competitiveness in the market place. These features will influence the building's longevity as an economically viable unit.

The roles involved on the Value Axis are situated in the sections between the value factors. These are filled by the people, who execute the work which affects the quality of Building Performance, and consume the resources which create the Building Cost of each section of the Value Axis.

Between the Hypothetical Minimum Cost and the Project Cost, there are the Project Executant Roles e.g., the suppliers and subcontractors.

Between the Project Cost and the Project Price, there are the Project Managers who include the Designers and the Management Contractors.

Between the Project Price and the Rental Price, there is the building Project Owner and his Real Estate Agents.

Between the Rental Price and the Users Value there are the Users of the Building.

In moving up the Value Axis, it is important to note that one role is supplying a service to another role and that the Cost to the receiver is the given Price from the supplier. Such price will be derived more from the bearable market price for that service at that time and at that location than derived from the Cost of provision of the service plus overhead and profit etc. of the supplier. Each role will be attempting to maximize its own profit segment of the Value Axis.

The evaluation of Performance/Cost of the Building by the Designer for the User or Owner of the project, should take into consideration the whole mesh of interrelationships between the roles using and supplying the constituents of that Performance/Cost. By so doing, the Owner, via his Designers, has the opportunity to optimize the Performance and especially Cost for each project at that time at that location.

Within this context, this can be executed by

(1) making an appropriately patterned search through the available roles requisite for his already designed project, or
(2) stimulating proposals, (a) coordinated or (b) uncoordinated, from industry which may propose to supply the Performance he seeks at a cost, which provides him with an acceptable building.

In situation (1) prior to design presentation to the owner, the designer will have to evaluate his choices for elements of the building against the skill capacity and costs of the possible project team roles available in the market place.

In situation (2)(a) if each proposal is coordinated by a role in the industry, the owner's designer will have to evaluate each for inefficiencies and/or omissions, prior to contractual acceptance. Usually such inefficiences are due to the promoting of proprietary components, which do not optimize the Users Performance, thus reducing the Building Performance and in some cases raise his life cycle costs.

In situation (2)(b), if these proposals are uncoordinated e.g., separate subsystem bids, the owner's designer will have to evaluate, then reconcile the overlaps and omissions between them as well as correct the inefficiences caused by the promoting of suboptimal proprietary components.

Evaluation of Building Element Choices Using the Value Axis

The chosen materials for the building element must be:

(1) at or above the required datum of technological performance
(2) at or below the stated cost budget

Given that these are achieved, what does each element choice contribute to the correlation and integration of the whole project as a desirable entity? Such evaluation can be assessed against the opportunity to:

(3) minimize Construction Inefficiency:

(a) by maximizing Modular Coordination to maximize repetition in the construction process and component manufacture and
(b) by communicating the most efficient construction process to the executant roles and the construction management roles.

It should be borne in mind that a conceptual efficient construction process is taken as the datum and each choice for each building element is evaluated against that datum. This facilitates overall efficiency of the construction process.

(4) minimize Project Price (Present Value):

(a) by consideration of the most appropriate project construction team in the market place for that location at that time for that project
(b) by consideration of the most appropriate contractual arrangements between the project roles
(c) by consideration of the most appropriate contractual arrangements between the project team and the owner and
(d) by maximum use of Modular Coordination to minimize the maintenance costs over the life cycle of the building e.g.,ease of replacement and repair of building components which wear out.

(5) maximize Competition Neutralization:

(a) see 4(d) above,
(b) by inclusion of components which have a low operating-cost to capital-cost ratio and
(c) by neutralization of maximum number of competitive features in the locality and

(6) maximize Competitive Advantage by inclusion of features which are desirable and unique in that locality.

Conclusion

It is in the building design process that evaluation of performance is at its most crucial for the overall success of the building project.

By solely considering the technological performance of materials in the evaluation of buildings it is probable that the best overall building performance is not achieved.

Consideration of solely the technological performance and the budget cost of each building element may be a correct beginning to such an evaluation but it is not likely to provide overall User Satisfaction from the whole project.

To attempt to achieve overall User Satisfaction from a building many other factors have to be taken into consideration.

The factors of the Value Axis point a way in which such further evaluations can be made and related one to another.

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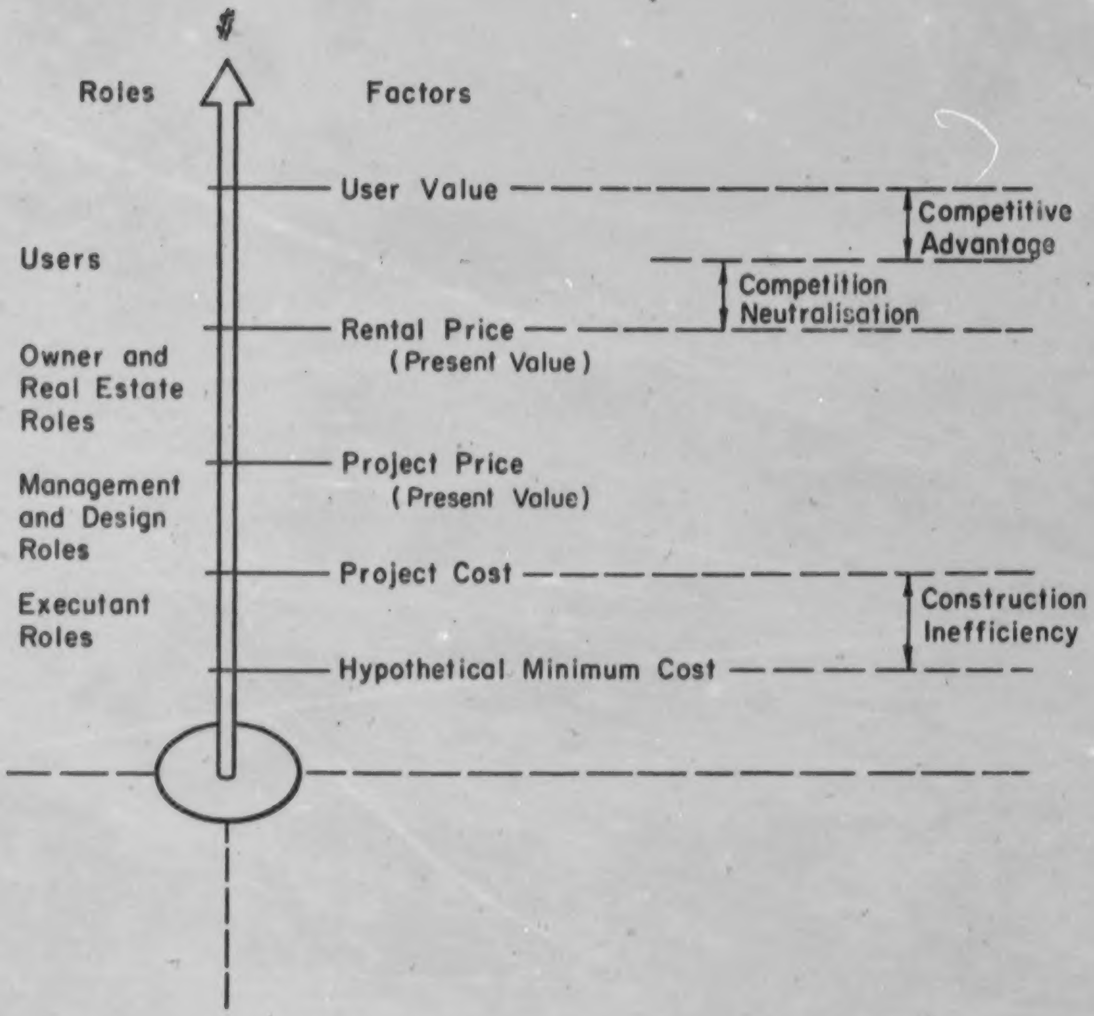
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Roles
Factors
User Value
Competitive Advantage
Users
Competition Neutralisation
Rental Price (Present Value)
Owner and Real Estate Roles
Project Price (Present Value)
Management and Design Roles
Project Cost
Construction Inefficiency
Executant Roles
Hypothetical Minimum Cost

VALUE AXIS

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ARCHITECTURAL ECONOMICS RELATED TO COMFORT, PRODUCTIVITY AND GLASS

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For many years, the most sophisticated and objective professionals have believed that thermal and visual "environmental factors" can exert a profound influence on the physical comfort and productivity of building occupants. Some experienced owners, such as the General Services Administration, believe that 90 percent of the owners' total cost in an office building can be charged properly against people and only about 10 percent against land, building and debt service. Experienced tenants regularly pay more money for carefully controlled and selected environments.

Glass "environmental factors" such as glass surface temperature, influence productivity and can be evaluated in a practical way. For exploratory use and for professional evaluation and criticism, an empirical people-productivity/glass-performance evaluation system is proposed. This evaluation system illustrates a practical relationship between glass "environmental factors", comfort and productivity. A comfort-productivity relationship equation is developed. A practical example illustrates the effect architectural glass could have on productivity and profits.

Il y a longtemps que les professionnels les plus avertis et les plus objectifs pensent que les facteurs d'environnement thermique et visuels d'un bâtiment peuvent exercer une profonde influence sur le confort physique et la productivité de ses occupants. Quelques propriétaires expérimentés, tels que l'Administration des Services Généraux, estiment que 90% des frais totaux supportés par le propriétaire d'un immeuble de bureaux peuvent être sans erreur mis au compte des gens, et 10% seulement au compte du site, de la construction et de l'organisme de prêts. Les locataires expérimentés paient régulièrement plus pour un environnement soigneusement contrôlé et choisi.

Les facteurs d'environnement du verre influencent la productivité et peuvent être évalués de façon pratique. Un système d'évaluation empirique de la performance productivité humaine/surface vitrée est proposé à titre de prospection et pour être soumis à l'appréciation et aux critiques des professionnels. Le système d'évaluation illustre un rapport pratique entre les facteurs d'environnement du verre, le confort et la productivité. On a développé une équation du rapport confort/productivité. Un exemple pratique à partir d'un bâtiment réel illustre l'effet que le verre architectural pourrait avoir sur la productivité et les profits.

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Key words: Building economics; capital costs; human comfort; human performance; insulated glass; operating costs; people costs; single glass.

1. Introduction

Peter Drucker, in his book "Managing for Results", states "Business results (profits) are obtained by exploiting opportunities" and to reveal these opportunities "we need to see the hard skeleton, the basic stuff that is the economic structure".

Sophisticated procedures and equipment now used in building design have enabled in depth studies of architectural economics. Designers and owners are aware that costs other than initial construction or capital costs have significant influence on the "total" building profit picture.

Gores,[1][2] stated, "if you build a million dollar high school,its operations budget will be about a million dollars every three years. Over a life of 60 years, the cost of the building will be only about 6 percent of the total cost".

Gores continued "To put it another way, when you add two teachers to the school staff, the salaries and benefits for 30 years equal the cost of a million dollar building. Yet school officials may discuss for five minutes consequences of adding two teachers, then argue into dawn the expenditures for a building. In short, building costs are chicken feed in the educational scheme of things".

The GSA's Public Building Service[2] report states,"An analysis shows that the life costs of the system (building) over 40 years are approximately:

92% - cost of people to process information (salaries)

6% - maintenance and operation of facilities

2% - first cost of the building"

The economic structure of costs shows that people expense is a major part of the dollars that go into total building costs.

Greater potential profit opportunities are revealed only when considering total building expense which includes capital costs, operating costs and people costs.

Professional economic consultants, administrative educators and government agencies are recognizing "a growing awareness of the interdependence of productivity and the general well being of employees fostered by well designed and aesthetically outstanding facilities".[3]

2. Capital Costs

To illustrate how total building costs relate to one another initially and after 10 years of operation, consider a 10-story office building.

Fig. 1 shows a 10-story office building with a total initial or capital cost of 4.5 million dollars. These costs are appropriated to various services and functions as illustrated. Let's assume the building details are as follows:

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[2] Figures in brackets indicate literature reference at end of paper.

Total Capital Cost - 4.5 million dollars
Total Floor Area - 150,000 sq. ft.
Rentable Floor Area - 105,000 sq. ft. (approximately 70% of total floor area).
Number of People Occupying the Building - 600
Total Glass Area - 30,000 sq. ft. (approximately 50% of exterior wall)

3. Operating Costs

With these costs distributed as illustrated in Fig. 1, consider the building as it would look with the operating expense added after ten years of operation. Based on the 1970 Office Building Experience Exchange Report, [4] the average annual operating expense for a typical building in 1970 was approximately $4.00 per sq. ft. of rentable floor area. Multiplying this expense by the rentable floor area of 105,000 sq. ft., we have an annual operating expense of 0.42 million dollars. Over a ten year period this becomes 4.2 million dollars. Thus, as shown in Fig. 2, the percent of total cost (4.5 + 4.2 = 8.7 million) attributed to operating expense is 48.0 and the percent of total cost attributed to capital cost is 52.0.

EXAMPLE: Effect of Operating Costs on Building Profits

Consider the cost of a high quality exterior wall with improved thermal insulation relative to a lower quality wall (reflective insulating glass relative to clear single glass, perhaps). With the higher quality wall, there is a 12 percent drop in HVAC*cost, a 2 percent drop in building operating cost and a 10 percent increase in architectural construction cost. The effect on overall costs is shown in Table I.

TABLE 1

COST ELEMENT	PERCENT CHANGE IN ELEMENT	OWNING AND OPERATING FACTOR FROM FIG. #2	% CHANGE IN COSTS
HVAC	-12%	6.3%	-0.76%
Operating Costs	- 2%	30.0%	-0.60%
Architectural	+10%	9.4%	+0.94%
Total Change in Owning and Operating Costs			-0.42%

In other words, the improvements in the thermal insulation as described above will result in 8.7 million dollars x 0.42% = $36,500 net savings to the owner of the building in ten years.

Increased capital expenditures for design improvements in structural, architectural or more sophisticated mechanical or electrical equipment are less significant cost-wise when the future operating cost of the overall building is considered.

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* Heating, Ventilating and air conditioning.

4. People Costs

Now, let's consider how people costs are related to overall building costs.

Recall that the number of people occupying this office building will be 600. Assuming that the owner's expected payroll and benefits for 600 employees average $5 per hour (holidays, medical, social security, etc. - adjusted for merit and inflationary increases in expenses over a ten year period), the owner has an expense of 63 million dollars.

(600 people x $5 per hour x 2,100/hours per year x ten years = approximately $63,000,000).

Thus, as illustrated in Fig. 3, the "real" total cost of a building includes people expense, operating expense and capital costs. A total of 71.7 million dollars is invested by the owner/tenant of the building.

Capital Costs	4.5 million	6.3
Operating Costs	4.2 million	5.9
People Costs	63.0 million	87.8
TOTAL	71.7 million	100%

Considering this total picture, improvements in the construction or during the capital cost stage of a building which positively affect people expense could generate substantial savings over the life of the building for the building owner/tenant. A basic economic analysis is required of building construction, building operating and building people expense before real opportunities can be recognized and included during the design stage of the new office building.

Now that we know where the money goes (or a good portion of it) let's take a look at people and find out what influences people expense because "people cost money".

5. People Influence on Building Profit

Researchers and scientists the world over have documented requirements for a "comfortable environment" for people. The American Society of Heating, Refrigerating and Air Conditioning Engineers has developed a comfort standard 55-66 which provides specific conditions required to achieve comfort. Conditions such as dry bulb temperature,73 to 77F, relative humidity,20 to 60 percent, air velocity,45 ft. per minute maximum and 10 ft. per minute minimum, mean radiant temperature (MRT),70 to 80F. Heating, air conditioning, ventilating and system control manufacturers can provide equipment to achieve these conditions. Now, however, the building owner/tenant may ask; what does providing this comfort mean to me? What is my return on investment?

The answer is not yet known. But some indicators are out. Many have experimented to determine the effect of comfort on human performance. In 1962 Charles Peccalo [5],after three weeks of testing two groups of 44 fourth grade students, found that the children in an air conditioned environment displayed greater progress than children in a non-air conditioned environment.

In rigorously controlled experiments at Kansas State University[6] 72 college students, when tested between a temperature range of 62F to 92F, learned most easily and with minimum error rate at 80F. (Researchers attributed the relatively high optimal temperature to the experiment's timing. It was conducted in October before the onset of cold weather. Thus the students had apparently remained adapted to summer weather, physiologically tuned to higher temperature.)

In tests conducted at the National Swedish Institute for Building Research [7] on a group of ten year olds, performance declined in language learning, arithmetic ability, spelling, reading speed and comprehension at temperatures ranging from 81F to 86F.

Industry has long been convinced that controlled comfort environment improves both office and plant workers efficiency-productivity.

Again, from the building owner/tenant:

"Yes, comfort control is fine. I believe it helps but - how much? How sensitive are people to degrees of comfort? Isn't it enough that cool air in summer is provided?"

R. D. Pepler,[8] of Dunlap and Associates, in a report on a test conducted in Portland, Oregon, on school children, sixth grade through ninth grade, stated that smaller temperature variations (2F to 3F) affected academic performance more in air conditioned environment schools than larger temperature variations (8F to 10F) in non-air conditioned environment schools.

Hence once a comfortable environment has been established and people "climatized" to that environment, it is essential to maintain a set condition to assure maximum productivity.

Thus to the building owner/tenant we suggest two significant steps to maximize people profit opportunities through improved comfort/productivity.

1. Provide a controlled comfortable environment
2. Maintain minimum variation within this controlled environment.

How can this be done? How much is it worth?

5.1 Comfort Environmental Effects on Building Profits

Let us consider Item 1. - Provide comfort controlled environment (to improve productivity.)

Harry Johnson, [9] suggests a comfortable environment may improve office worker productivity by 15 percent.

In the comfort sample problem illustrated in Fig. 3, the people cost represents 87.8percent of all building costs for a ten year period or 63 million dollars. If Johnson is on target, the HVAC system (a portion of building capital costs contributing directly to comfortable environment) will provide an environment for increased people productivity of 15 percent.

EXAMPLE: Comfort Improves Productivity

HVAC Portion of Initial Capital Costs is 13% (Fig. 1)
or 13% x 4.5 million = $ 585,000

Investment benefit to owner/tenant after ten years
or 15% x 63 million = 9,450,000

Is it Worthwhile?

Future worth of $585,000 @ 10% interest 1,520,000
Over a period of ten years is $585,000 x 2.6
(Future Worth Factor)

That is - $585,000 invested today at 10% interest will be worth 1.52 million dollars after ten years.

Savings to the Owner/Tenant

9,450,000 - 1,520,000= 7,930,000

This represents a sizable difference. However if estimated people benefit is off by a factor of 5, the equipment is still worthwhile.

5.2 Environmental Variation Effect on Building Profits (Glass Performance and Effects)

Now consider Item 2 - Maintain minimum variations within a controlled environment (to improve productivity).

Variations within the controlled space can be caused by several factors. Experts often criticize glass as a culprit causing variations of system control within the space such as drafts, brightness and cold walls. So, for convenience, let's consider glass. (Air conditioning controls, insulation, lighting, and other manufacturers can use this same reasoning when considering more sophisticated environmental control equipment, devices or materials).

The suggestion that glass thermal and visual performance influences the productivity of building occupants is generally accepted but few consider this a practical consideration since experts have been unable to develop a standard or measure of influence. The experts can help us though all are not in agreement. How much then can productivity be influenced by glass performance?

By assuming glass can cause fluctuations within a controlled environment which influences human comfort which, in turn, influences productivity, a scale or measure of performance requirements can be established. Glass characteristics which influence comfort, hence productivity, are color, glass surface temperature, brightness (light transmission) and energy transmission. The following is a suggested procedure for determining the effect of glass performance on productivity or the long-term influence of glass costs on "real" total building costs.

Unlike the statement by Johnson, no one has suggested a percentage of improved productivity if insulating glass is used instead of single glass.

Olivieri, [10] suggests a procedure which evaluates air conditioning systems by calculation of a comfort coefficient. This procedure also can be used to evaluate the influence of glass. Glass surface temperature is a major factor when considering occupant comfort. If the glass surface is too cold, heat is lost from our bodies by radiation and we become cold. If the surface is too warm, heat is absorbed by our bodies and we become warm. Olivieri states a comfort coefficient of 75% is the best that can be achieved considering an office building perimeter of two-thirds single glass in a northern climate and an air conditioning system consisting of overhead double duct with perimeter radiation. However, Mr. Olivieri also states "if we change the glass to double or insulated glass... this would give a 95 percent system." Here, then, is a method for rating glass performance and its influence on people productivity based on professional observations.

Johnson has stated that the use of air conditioning creating a comfortable environment may increase people performance by 15 percent. Olivieri has stated that within the controlled environment the comfort rating will be improved from 75 percent to 95 percent if insulating glass is used rather than single glass. Thus, we can develop the ratio:

$$\frac{\text{Comfort A (single glass)}}{\text{Comfort B (double glass)}} = \frac{\text{Productivity A}}{\text{Productivity B}}$$

or

$$\text{Productivity B} = \frac{\text{Productivity A} \times \text{Comfort B}}{\text{Comfort A}}$$

$$= \frac{15\% \times 95\%}{75\%} = 19\%$$

or Productivity Increase[3] from single glass to double glass of:

$$19\% - 15\% = 4\%$$

That is, the increase in comfort rating of double glass versus single glass is proportional to the increase in people performance of double glass versus single glass. Thus, assuming Johnson's suggested increase[3] in people productivity of 15 percent is based on the 75 percent rating of single glass, then a people productivity of 19 percent would be based on a comfort rating of 95 percent with insulating glass or a maximum productivity increase due to glass of 4 percent.

EXAMPLE: Comfort Environmental Variations on Building Profit

Recall the example building described earlier and illustrated in Fig.3. Assuming a 4 percent people performance improvement when double glass is used in place of single glass, we find:

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[3] Footnote: This assumes that Johnson's suggested increased people productivity performance was based on air conditioning and single glass. If this assumption is not valid, we can then assume that Johnson's suggested 15 percent improved productivity was with air conditioning and double glass. A relationship of double and single glass and people productivity could be developed for this case also. However, for this paper, we will proceed with the former assumption. Another assumption is that the double glass is equivalent to the highest performing glass available on the commercial market (low heat gain, warm surfaces in winter, cool in summer, low light transmission, etc.)

The building glass area is 30,000 sq. ft. Assuming an INCREASE of initial glass cost for insulating glass is $3.40 per sq. ft. or

$3.40 per sq. ft. x 30,000 sq. ft.	=	$ 102,000
Investment Benefit to Owner/Tenant Over ten years is 4% x 63 million	=	2,520,000

Is it worthwhile?

Future worth of $102,000 @ 10% interest

over a period of ten years is $102,000 x 2.6 (future worth factor)	=	265,000

that is, $102,000 invested today @ 10% interest will be worth $265,000 after ten years.

Savings to the Owner/Tenant

$2,520,000 - $265,000	=	2,255,000

Other benefits of high performance insulating glass are reduced initial heating and cooling equipment costs and reduced annual operating costs. Often these alone can offset the increased cost of the glass. Then, improved people productivity is 100% savings to the owner/tenant. The comfort benefits of high performance insulating glass can become significant owner/tenant savings.

Other relationships with glass products single and double glazed can be developed with the use of Table II which provides information on one brand of commercial glasses which fall within the limits of 0 to 4% improved productivity.

TABLE II
GLASS PERFORMANCE/PEOPLE PRODUCTIVITY RELATIONSHIP

SINGLE GLASS	PRODUCTIVITY %* INCREASE
1/4-inch Clear	0
1/4-inch Tinted	1.0
1/4-inch Reflective	1.5
INSULATING GLASS	
1-inch Clear	2.5
1-inch Tinted	3.0
1-inch Reflective, low performance	3.5
1-inch Reflective, high performance	4.0

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*Assuming a high performance heating, cooling and ventilating system.

6. Summary

The National Bureau of Standards' report "Performance Specifications for Office Buildings" [11] states:

> "it is evident that the building cost reductions can have only limited benefits, while a more thorough analysis of users needs and ultimately, behavior, is potentially the more beneficial."

We have shown the potential benefits of occupant comfort.

We have shown studies that indicate comfort has a positive influence on occupant productivity.

We have illustrated a technique to establish performance requirements for architectural glass products to improve occupant comfort.

The challenge now is to provide techniques of evaluating productivity to determine the value achieved through improved comfort. Only then can maximum profit be realized by the building owner/tenant.

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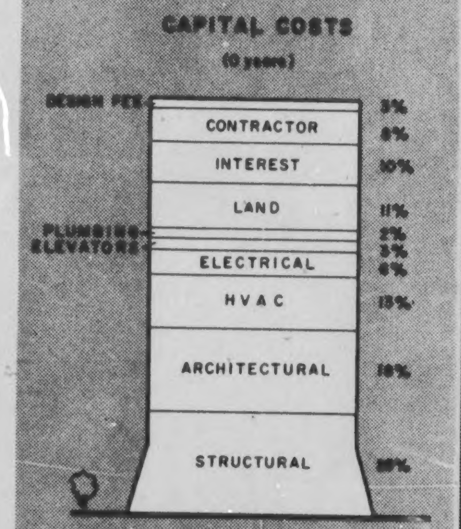
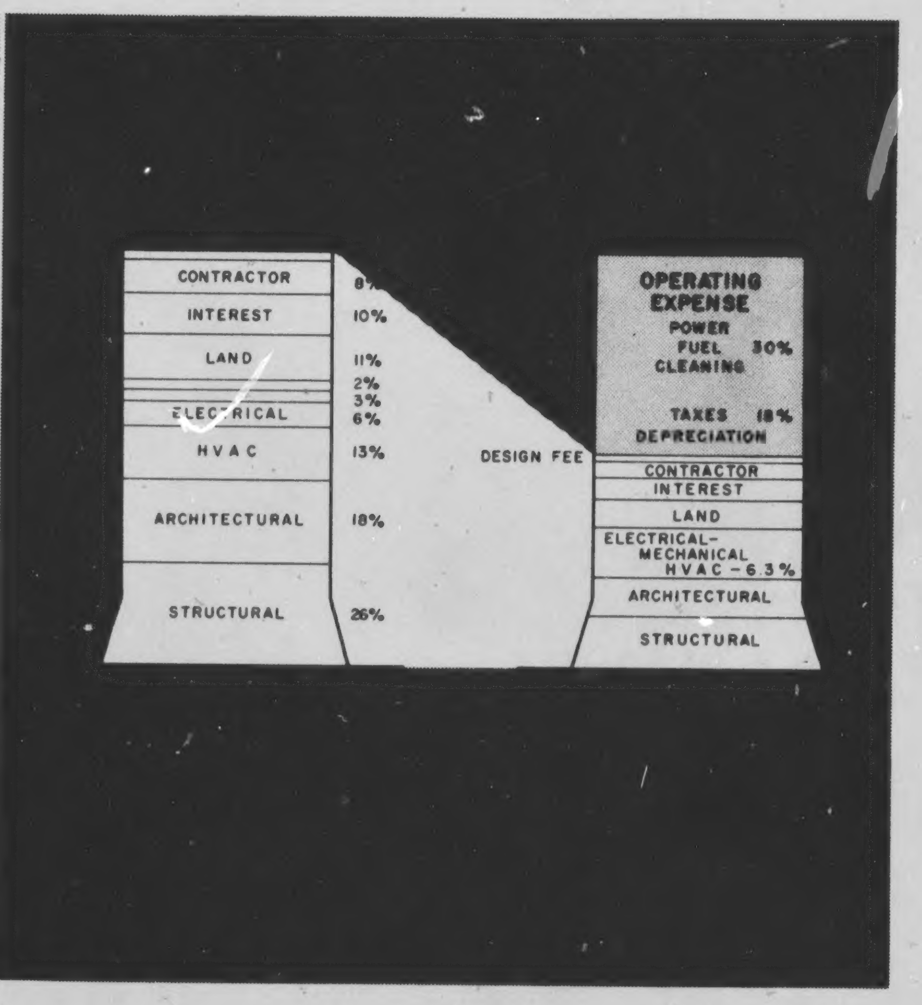

CAPITAL COSTS
(10 years)
DESIGN FEE
CONTRACTOR
INTEREST
LAND
PLUMBING
ELEVATORS
ELECTRICAL
H V A C
ARCHITECTURAL
STRUCTURAL
3%
8%
10%
11%
2%
3%
6%
13%
18%
26%

4.5 MILLION
U.S. Dollars

FIGURE I
10 STORY OFFICE BUILDING


CONTRACTOR
INTEREST
LAND
ELECTRICAL
H V A C
ARCHITECTURAL
STRUCTURAL
8%
10%
11%
2%
3%
6%
13%
18%
26%
DESIGN FEE
OPERATING EXPENSE
POWER
FUEL 30%
CLEANING
TAXES 18%
DEPRECIATION
CONTRACTOR
INTEREST
LAND
ELECTRICAL-MECHANICAL
HVAC - 6.3%
ARCHITECTURAL
STRUCTURAL

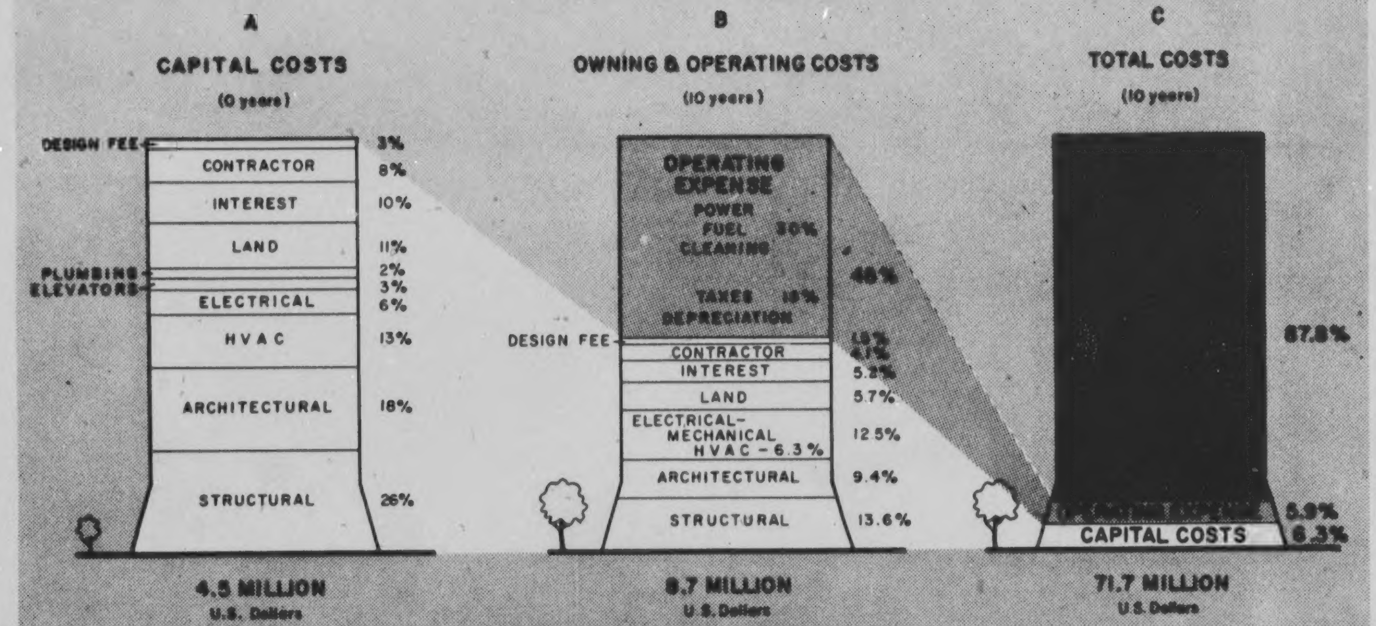


FIGURE 3 – 10 STORY OFFICE BUILDING

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

The Notion of Performance in Building: Building Requirements

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A building is built for a given purpose, i.e. to meet the requirements of the man for whom the building is built, the user's requirements. These are related to the whole building and can be expressed in terms related to man by numerical figures for the best known requirements such as physiological and economic ones, and by words in other cases, i.e. for psychological or sociological needs, roughly speaking.

To meet the users' requirements, a building has to present a set of physical (including chemical, geometrical, and mechanical) properties. Various sets of physical properties may be suitable to meet the same set of requirements.

Generally speaking a building is built of elements, and elements are made of products (raw materials, semi-finished products, sections, components).

It is possible to relate the properties of a built element to the properties of the constituent products, by considering the various physical characteristics and also the compatibility of adjacent parts.

Some details will be given on the users' physiological, psycho-sociological and economic requirements at the level of the whole building; on absolute needs and relative requirements; on the variation of requirements in space and time.

Un bâtiment est construit dans un but déterminé, c'est à dire pour satisfaire les exigences de celui pour qui le bâtiment est construit, les exigences de l'utilisateur. Ces exigences se rapportent au bâtiment dans son ensemble et peuvent être exprimées en termes relatifs à l'homme par des chiffres pour les exigences les mieux connues telles que les exigences physiologiques et économiques et par des mots dans les autres cas, c'est à dire grosso modo pour les exigences psychologiques et sociologiques.

Pour satisfaire les besoins de l'utilisateur, un bâtiment doit présenter un ensemble de propriétés physiques (ce mot veut aussi dire ici chimiques, géométriques et mécaniques). Plusieurs ensembles de propriétés physiques peuvent permettre de satisfaire le même ensemble d'exigences.

Un bâtiment est fait d'éléments et les éléments sont faits de produits (matière première, produits semi-finis, composants).

Il est possible de déterminer les propriétés d'un ouvrage en considérant les propriétés du produit qui le composent, leurs diverses caractéristiques physiques et aussi la compatibilité des éléments adjacents.

Quelques détails seront donnés sur les exigences de l'utilisateur au niveau du bâtiment tout entier, physiologique, psycho-sociologique, économique; exigences absolues et relatives, variation des exigences dans l'espace et dans le temps.

Key words: Assembly; compatibility of components; physical properties of a building, of a product; users' requirements.

A building is erected, obviously, to attain a certain objective, to meet certain needs. These needs are those of the person for whom one builds: the needs of the user.

It is possible to describe fairly completely what is expected of the building one is putting up. These needs are in part of a general kind, that is there are needs common to the family of buildings considered: if it is a dwelling, there is a set of needs common to dwellings - if it is a hospital, there are also common needs - if it is a stable or a piggery, there are common needs ; also if it is a factory for making precise electronic components. Then, there is the specific program for each operation from which arises the particular needs of the particular user.

These needs are not expressed in the physical properties of such and such a part of the construction, or even of the whole. What one wants to get when building a dwelling is to have a space within which one has certain conditions of comfort or safety, which offers certain areas with a certain articulation between the rooms, where one has the fittings necessary to the life that one wants to lead in this dwelling. We will come back to this in another paper in this symposium. It is not a question at this moment of fixing values of insulation or of strength. What are wanted are temperatures, sound levels, degrees of safety.

At the moment, when one proceeds to devise the solution to the problem set by this statement of the needs of the user, one has to pass from data relating to man to the physical data of the building and of its parts.

In another symposium paper entitled "What are the natures of perfor - mance and evaluation for the three levels : building, components, materials?" the differences in expression of the needs of the user, of the performance of the building as a whole, of the physical qualities of the components and of the properties of the materials,are further developed.

This paper is devoted to what is demanded of the building as a whole, that is to say the satisfaction of the user's needs.

A distinction is often made between needs and requirements, or rather one tries to distinguish between the needs one would like to satisfy if one had all possible means at command and the more realistic needs which one can hope actually to meet.

In my opinion, the only thing to consider is the second, It is not very useful to consider things that one cannot achieve. The "building requirements" are needs that one is going to try to satisfy, and if they have already been fixed at a certain level, it is because it is already known by experience that this can just about be achieved with the economic and technical means available.

The general needs of man in his dwelling, to take an example, have been the subject of a list drawn up by the CIB working commission W 45 which has been published in the book of the 5th CIB Congress, in BUILD, and in French in the Cahiers of the CSTB.

This list is not perfect, but all the same, it is relatively complete.

The requirements of users are divided into four kinds : requirements of a physiological kind, those of a psychological kind, those of a sociological kind, and economic requirements.

The aim of the first is to ensure safety in relation to dangerous phenomena such as asphyxia, cold, collapse of the building, and to ensure comfort in relation to the same phenomena.

The second, which is related to the first, represents the individual needs which are proper to thinking beings. In talking of them one could speak of mental hygiene or of mental comfort. Such for example are the quality of lighting, the dimensions of rooms.

The sociological requirements are that the dwelling should be capable of suitably sheltering the life of a family, and therefore that it should contain the number of rooms with the desired dimensions, suitably connected with one another, and providing all the equipment necessary to all the actions of a family and of the individuals of which it is made up.

This is easy to transpose. If we are dealing with a school there are teaching requirements; if a hospital, there are clinical requirements, etc..

And lastly, the economic requirement which completes the problem is that of erecting the building and making it work for a given expenditure. We shall meet here the idea of the final cost which takes account of the initial outlay, of operating costs, maintenance, replacement, and perhaps even ease of conversion.

Among these requirements there are absolute requirements which in general are physiological requirements and relative requirements : these are the psychological and sociological requirements.

The level of the relative requirements ought to be fixed by a minimum threshold below which one does not wish to go. On the other hand, the safety requirements ought to lead to the fixing of margins of safety. Bearing in mind that the building requirements ought to find expression in obligatory texts - laws and regulations - these are therefore thresholds for the relative requirements, and factors of safety, for the absolute or safety requirements which one ought to find in a regulation of the requirement or performance type.

It is necessary to consider several levels of quality in the satisfaction of the different needs ? We think that this is a refinement difficult to achieve. And we ought not to forget that, in each building, the general requirements are accompanied by a program of special requirements and that therefore, if one wants to refine, or on the contrary if one wants to go below the usual limits on any given point, that should be specified in the special program.

I do not know whether what is dealt with here is what is commonly understood in the United States under the term building requirements. I hope so, but in any case I consider that what one asks of a building is that it should satisfy the user's needs, and that it is not possible to write down the building requirements in a suitable and correct way except by considering the user's requirements. If in fact it is accepted that the building requirements are expressed in terms of the physical qualities of the construction, that would mean that one had made an a priori choice of a type of construction. In reality, to meet a given set of user's requirements there are many different possible buildings. The very spirit of the performance concept, we would say in French the "esprit exigentiel", is to give equal chances to all solutions. For that it is absolutely indispensable not to express what one expects from the building as a whole otherwise than in terms of the user, that is, what the building is going to do for the man, or for what will be put in it, and not in terms of the physical properties of the building.

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What are the Natures of Performance and Evaluation for the Three Levels : Building, Components, Materials

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For a whole building what is required is the satisfaction of the users' requirements. For example for a dwelling the requirements are temperature, noise level, illumination level, air purity level, convenience of internal space, convenient relationship between the various rooms and an adequate view from the inside, etc...

The means of evaluation are the sciences which relate the physical properties of the building to the effect on the inhabitants, or reference to a long and satisfactory use of some techniques or direct proof by the real occupation of the building by users and the observations of the latter.

What is needed for components is that they possess the physical properties which enable the built elements to play their correct part in the building as a whole.

These properties are expressed in scientific terms, i.e., by reference to physical characteristics measured by any methods, in terms of technological indexes based on long experience or on tradition, or in terms of physical requirements. There is also the important problem of durability (cf. the paper on Agrément).

As for raw materials, it is not possible to have requirements of any sort by performance or otherwise, because there is no defined link between materials and a building. We can only judge a material + its shape, i.e., roughly speaking, a component.

Ce qui est exigé de l'ensemble d'un bâtiment c'est la satisfaction des exigences de l'utilisateur. Par exemple, pour un logement, les exigences sont: la température, le niveau du bruit, le niveau d'éclairage, le niveau de pureté de l'air, la convenance de l'exposition intérieure, etc...

Les moyens d'évaluation sont les sciences qui permettent de prévoir, à partir des propriétés physiques du bâtiment, l'effet produit sur les occupants, ou la référence à un long et satisfaisant usage d'une solution déterminée, on la preuve directe par enquête faîte sur les occupants d'un immeuble.

Ce qui est demandé des composants, c'est qu'ils possèdent les qualités physiques qui permettent aux ouvrages de jouer correctement leur rôle dans l'ensemble du bâtiment.

Ces propriétés sont exprimées en termes scientifiques, c'est à dire l'indication de leurs caractères physiques qui sont mesurés par n'importe quelle méthode valable, en termes de valeurs d'index technologiques, basées sur la longue expérience ou sur la tradition, ou bien encore en termes d'expérience directe. Le problème de la durabilité se pose alors (voir le rapport sur l'agrément).

Pour ce qui est des matériaux, il n'est pas possible d'exprimer des exigences d'aucune sorte par le moyen des performances ou autrement, puisqu'il n'y a pas de relation précise entre un matériau et un bâtiment. Nous pouvons seulement juger l'ensemble d'un matériau et de son élaboration, c'est à dire à peu près un composant.

Key words : Agrément; building components; durability; materials; performance; tests.

This paper is a sequel to the paper in this symposium on Building requirements. It sets out from the same considerations :

I. The construction as a whole

The problem that we are trying to solve is posed in terms of user's requirements, of what one should obtain from the building as a whole; that is that the requirements applying to the whole of the building will include, for example, a certain internal temperature and hygrometric condition, a sound level, a level of illuminance, a level of air purity, the suitability of the internal space, the suitability of the arrangement of the dwelling, an adequate view from the inside to the outside, etc..., and also a limited final cost.

The evaluation of the level of satisfaction of the user's requirements is carried out by comparing the result obtained with what was demanded. In some matters this is easy since it is a question of measurable quantities : there is nothing difficult in comparing the sound level inside the premises with what was asked for. It is not difficult to measure illuminance. It is

not difficult to measure temperatures. Nor is it difficult to establish whether the construction has cost more than was specified or to establish that the operating costs, that is the expenses for heating, lighting, and power, are greater than the sums allocated.

On these points it is possible not only to check the results once construction is finished,but also, by means of calculation, to forecast from the plan, to a sufficient approximation, the magnitudes of temperature, noise and energy consumption. The designer therefore has the means of checking in the course of his study whether the scheme he is designing is in fact the answer to the requirements.

On the other hand, in the psychological and sociological domains, things are not so easy. It is true that when the building is finished one can find out by enquiry from the users of the building whether one has succeeded in giving them what they were hoping for, although one does not often do it. Such enquiries are long and costly, and their results are always marked by some uncertainty. But, what is more embarrassing, is that we do not really know how to judge the quality at the design stage, and this derives from the low level of our knowledge in the fields of the human sciences applied to building. This means that, apart from the empirical reproduction of solutions that have already more or less given satisfaction, we have to proceed in the dark. To put it another way, new solutions, if they are really new, should be used with caution and be subject first of all to experimentation on suitable samples before being applied generally. This is in contrast to that in the field of physics where our scientific level allows us to forecast the results of solutions that are frankly new.

To be able to evaluate a design as a whole, it is not necessary that all its details should have been settled. It is sufficient that the overall intent of the design, which we call the "synopsis" of construction, should have been determined and the manner in which the various built elements which make up the construction are going to contribute to the satisfaction of the requirements should be known. By built elements we understand the main parts of the building such as foundations, external walls, load-bearing structure, partitions, and the various kinds of fittings. It is sufficient to have determined the overall physical or geometrical qualities,(I am taking physical in the widest sense, that of actual material,)to be able to evaluate the response of the building.

2. The built elements and the components

This overall orientation of the design, this "synopsis", will be given material form by the components entering into the construction of the built elements: cladding panels, partition panels, windows, prefabricated bathrooms, pipes, boilers, etc...

What we need to know is whether the assembly of the components which make up an element has the desired qualities so that the built element itself can have the desired qualities. For example, according to the "synopsis", the external surfaces element ought to confer to the building an overall thermal loss of a certain value: 1.2 kcal/ hr - °C - m^3.

This external surfaces element will be composed of a roof and of cladding components: some transparent, the windows; others opaque, the solid panels or the gable ends. Therefore, these components ought to have insulation coefficients such that in sum the loss from the external surfaces is what was counted on. Moreover it must not be forgotten that there are joints between these components and that from the heat loss point of view, these joints can play a part, either because they are thermal weak points, or because there would be leakages which would increase the rate of air change.

A first point therefore : a component is not evaluated in the absolute. It is evaluated in relation to the part it will be called upon to play in the constitution of a building element, the qualities of this built element depending on the "synopsis" or overall intent that has been made.

3. Components properties

The components are evaluated in consideration of their required properties. They are of various kinds :

- Material properties, measurable quantities such as sound insulations, thermal resistances, reflection coefficients, mechanical strengths.
- Qualities or quantities that can be described only, characterized by indices or subjective judgements on material qualities, as for example : quality of appearance which one might try to express in physical terms, but which it is more practical and more usual to express in common terms.
- And lastly durability which is a quality that is required of each component and which therefore arises with each of them, but which poses special problems of assessment.

To summarize, the components are assessed according to the way in which a certain number of their physical or material properties correspond to what is expected of them if they are to play their part in the built element as a whole, which in turn will play a fixed part in the general construction as designed in the "synopsis".

4. Determination of components' qualities.

The determination of the qualities of the components can be carried out:

- by measurement of defined quantities,
- by identification of technological indexes by means of tests which are standardized but more or less arbitrary,
- by observation of behaviour in practical conditions (that is to say in buildings); or in the laboratory, by tests in semi-practical conditions, where one tries to reproduce natural conditions, although at the cost of a certain degree of standardization.

It is these semi-practical tests which are correctly described as performance tests.

5. Difficulties of definition and assessment of durability

The causes of lack of durability are essentially :

- excessive forces due to applied loads,
- excessive forces resulting from differential movements of adjacent components, movement due to the components themselves or caused by climatic variations ,
- destruction of the material itself by solution, corrosion, photo chemical reaction...

The first two causes can be more or less controlled and their effects predicted although the building industry often does not pay enough attention to them. On the other hand the disintegration of matter by corrosion or aging is generally impossible to predict for new materials, all the more so because in a general way chemists do not much concern themselves with a durability of the magnitude required by the building industry. The durability we need is measured on the scale of dozens of years; ten years is the minimum, and most of our usual materials last 30 to 50 years. Components which would last for a lesser time ought also to be much cheaper. Everybody knows that it is not easy to find materials cheaper than concrete, steel, and even timber.

An assessment of the durability of the component parts of a building and therefore of the building as a whole, should be sought first of all by making the maximum use of the scientific knowledge we possess. However, when dealing with new materials, there will remain a gap so longas these materials are sufficiently unknown to be called new. It is this gap that we seek to fill by means of agrément, that is to say by a judgement of impartial experts in the light of all that can be gathered from measurements, technological tests, "tortures" (that is to say tests that do not correspond to actual use but which may be indicative of the behaviour of the material), and from examples of actual use.

A paper in this Symposium is devoted to agrément : "Technical evaluation of components : agrément".

6. Sections and materials

The components themselves are manufactured from sections and from materials. We propose to consider that the difference between a component of a building and the sections and materials is that the component has one or more well-defined uses in building, while one does not know a priori what the section or material will be used for.

Thus a cladding panel is a component, but so also is a flooring tile and also a jointing mastic, while a plank of wood, cement or a glue are sections.

The distinction is important because I am going to maintain that it is not possible to evaluate a material if we do not know what its exact use will be: I am saying that it must be evaluated in relation to a defined use in building. Very precise specifications for a material can be given, in a standard for example, and it can be said whether the material does or does not conform to the standard. But it is impossible to know whether this material, whether or not it meets the standard, is suitable for the manufacture of a given component or structural part unless this component and this structural part are known.

To take a common example, a glue that is perfectly suitable for use in a dry atmosphere can be disastrous when used to bond an external cladding. If I specify the use of the material and say glue for external cladding, then I can assess its quality. In reality this glue will be included in the assessment of the structural part "bonded external cladding".

Materials do not therefore have to be evaluated in the absolute.

7. Levels of requirements and evaluation

It will be seen that there are two useful levels of requirements and of evaluation :

- that of the whole building
  - Requirements = User's request,
  - Evaluation = measurement, calculation, observation.
- that of the components
  - Requirements = Physical properties,
  - Evaluation = Measurements and calculations
    - technological index
    - Natural tests and performance tests
    - Agrément.

Materials cannot be considered except in relation to a definite use in building, and then they become in a way components.

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Techniques For Developing Performance Specifications For Buildings

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A tested technique is offered, which can serve as a generating model for performance specifications for any building type. The technique recognizes the primacy of the user's needs as the generator of information, while acknowledging that manufacturer's information requirements must be formatted in different terms. A matrix is used as a display device to show the set of all possible environmental characteristics for all possible subsystems.

The environmental characteristic' headings are: Conditioned air, Illunination, Acoustics, Stability, Durability, Reliability, Safety, Activity support, Maintainability, Esthetics, Waste management, Potable water, Food handling, Communication, Accessibility.

The Building subsystems whose performances must satisfy these requirements are: Structure, HVAC, Finished floor, Finished ceiling, Luminaires, Space dividers, Exterior walls, Plumbing Utilities, Sanitary fixtures, Food services, Cleaning systems, Energy source, Energy systems, Transportation systems, Roofs, Windows, Doors, Security systems, Sealant systems, Communication systems, Materials handling, Waste removal.

Each intercept is examined for interaction betweem demand (the user's needs) and supply (the capability of the subsystem to respond to, or alter the demand). Where an intercept is seen as interactive, three kinds of information are generated -- a Requirement which is a prose statement of the specific need, Criteria, some measure of the acceptable range of solution, and Test Method, the mechanism whereby surety of performance is guaranteed. A method of correlating Requirements, Criteria, and Test Methods into performance specifications by subsystem is described.

This technique attempt to deal with physiological requirements only and some discussion is presented for its applicability to psychological and sociological requirements.

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[1] Chairman, Graduate Program and President, respectively.

On propose une technique contrôlée qui peut servir de prototype pour les spécifications de performance de n'importe quel bâtiment. La technique admet la primauté des besoins de l'usager comme source d'information tout en reconnaissant que les exigences d'information des fabriquants doivent être formulées en termes différents. On se sert d'une matrice pour mettre en évidence toutes les exigences possibles pour tous les sous-systèmes possibles. On définit l'environnement selon: Climatisation, Eclairage, Acoustique, Stabilité,Durabilité, Fiabilité, Sécurité, Support d'activité, Entretien, Esthétique, Assainissement, Eau potable, Manipulation de nourriture, Communication, Accès.

Les systèmes de construction dont la performance doit satisfaire ces exigences se rapportent à: Structure, Chauffage et climatisation, Réseaux divers (eau, gaz, électricité), Revêtements de plancher, Revêtements de plafond, Luminaires, Murs de refend et cloisons, Murs extérieurs, Tuyauterie, Equipement sanitaire, Services d'alimentation, Systèmes de nettoyage, Source d'énergie, Systèmes énergétiques, Systèmes de transport, Toits, Fenêtres, Portes, Systèmes de sécurité, Systèmes de joints, Systèmes de communication, Manipulation de matériaux, Systémes d'assainissement.

On examine chaque division en regard de l'interaction entre la demande(les besoins de l'usager) et l'offre (la capacité du sous-système de satisfaire ou de changer la demande). Si une division révèle une action réciproque, 3 sortes d'information sont livrées: - une *exigence*, qui est une déclaration verbale du besoin spécifique; des *critères*, soit une détermination de la gamme des solutions acceptables; et une méthode d'essai, soit le mécanisme qui garantit une sûreté de performance. Une méthode de corrélation des exigences, critères et méthodes d'essai en spécifications de performance par sous-systèmes est décrite.

Cette technique se limite aux exigences physiologiques et une l'on tente d'examiner son application possible aux exigences psychologiques et sociologiques.

Key words: Environmental characteristics; performance; Performance specifications.

1. Definitions and Examples

Performance specifications state in precise terms the characteristics desired by users of a product's or system's performance without regard to the specific means to be employed in achieving the results. Such specifications have recently come into use as mechanisms for procuring building subsystems *and* evaluating their performance.

Performance specifications do not describe dimensions, materials, finishes, methods of manufacture -- they describe the performance attributes of building subsystems as required by someone -- that "someone" should be the user/consumer. They delegate responsibility for the actual design or selection of the product or system to someone other than the Architect or Specification Writer -- that "someone" is normally the system manufacturer and his design staff.

In normal use, traditional, or "prescriptive" specifications are a way of assuring that what is procured will be identical to some "model" which has given satisfactory performance in the past. Prescriptive specifications often prescribe the materials of which the object is to be made, the dimensions it must have, the finishes and the shapes, how it shall be installed, and in many cases who shall make it.

For example, in specifying a 10" brick cavity wall with running bond, we will accept as a solution only a 10" brick cavity wall with running bond. Yet we have selected that specification, whether we know it or not, on a performance basis. We wish a wall which has the following characteristics:

- stability against lateral and vertical forces
- sound attenuation and other acoustic qualities
- thermal insulation
- color and texture
- surface imperviousness to weather

We have found, in the past, that a certain solution (a brick wall) will do this specific job and when we are faced with the same problem, we draw on our experience and select that solution again. And yet, we are really seeking a certain level of performance. EVERY CONVENTIONAL MATERIAL SPECIFICATION IS BASED ON AN IMPLICIT PERFORMANCE SPECIFICATION. Prescriptive specifications are only a convenience. They are also a constraint to innovation, in that only a very narrow range of solutions to any one problem is acceptable at any given time, even though many solutions are available which would give equal (or better) performance. Therefore we have developed an aid to this process, and that aid is the Performance Specification.

As a specific example of a (part of a) performance specification, let us cite the Public Buildings Service Performance Specification for Federal Office Buildings (National Bureau of Standards 1970):

> "control air motion: this sub-system in use shall distribute air to the space such that air motion in the Occupied Zone shall be no less than 20 FPM nor more than 50 FPM. (Occupied Zone: all space from the finished floor to 78" above the finished floor excepting spaces closer than 2" to a Partition.) To be tested by field measurement of system prototype."

Note the structure of this statement: A user requirement ("control air motion") criteria (how much and where) and a test method (in this case, prototype testing in the field). These are the essential elements of the performance specification for the physical system -- if any portion is missing, it is not possible to use it as a procurement document.

2. The Uses of Performance Specifications

There are five important reasons for the development and application of performance specifications in the building industry.

2.1 The Voice of the User

We build all our buildings to satisfy the needs of the people who use them. Yet they are often unrepresented in the decision processes which affect how buildings are built and how they are to perform. Building today is a complex and fragmented process and much valuable information about user needs is lost, misplaced, or never generated to begin with. Performance Specifications, based on User Needs, are a way of retaining and amplifying "the voice of the user" in this complex building process. Where the specific needs of users are translated into performance terms and become the basis for procurement, there is an implicit guarantee that the user will be satisfied with the environments resulting from this process.

2.2 Information-Rich Procedures

Because the use of Performance Specifications relegates the responsibility for design decisions to points farther down in the building process, closer to the "output" end, it permits these design decisions to be made when more information is available to the designer -- the longer you can hold off making these decisions, the more you will know about the context of demands in which they will be made. Therefore, you are richer in information at the decision point.

2.3 Spur to Innovation

By avoiding the prescription of what a solution must be (the normal prescriptive specification), but rather describing what performance any solution must yield, the way is paved for innovation. By permitting any solution which meets the performance required, the building industry is permitted to explore alternative solutions to those now seen as "models".

2.4 Increased Cost-Effectiveness

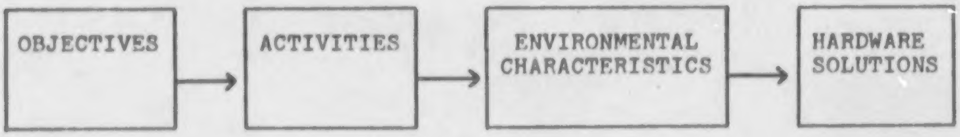
By permitting innovation, performance procurement may result in innovations which reduce first costs and/or life costs. Performance information makes it possible for industry to bring the costs of their products within the demand capability of the market by focussing on the basic performance characteristics of such products, rather than less relevant information.

2.5 Formal Evaluation and Feedback

By stating the desired performance explicitly in terms of criteria and test methods we are able to have (for the first time) a precise brief or program against which evaluations can be made. Since all design assumptions are in the form of Requirements, Criteria and Test Methods we are able to examine the building in use to evaluate the correctness of these assumptions. This forms the necessary information base for a system of formal evaluation and feedback, both now missing from the building industry.

3. The Development of Performance Specifications[1]

Performance Specifications are a function of the uses of the building -- the goals and objectives for which it is being built. The development of Performance Specifications may take place at four levels of application:



The goals or Objectives of the building to be designed are described. Each Objective probably requires a set of Activities to be performed by men/equipment/environments to achieve this Objective. Each Activity requires that some desired Environmental Characteristics be present to enable the Activity to be performed. Each Environmental Characteristic is supplied and controlled by some Hardware Solution.

For each step in this process, we must be able to measure the phenomena in some useful way in order to describe it, and to transfer useful information to the next level.

In specifying Hardware Solutions, we use as measures concepts like size, shape and materials and we accept only that solution which embodies the specified characteristics. A specification example would be a lighting fixture, and is the traditional specification method.

In specifying Environmental Characteristics, we use as measures concepts like illumination, stability, and air quality, and we accept those solutions which exhibit the performance desired. We are specifying the performance which hardware must generate. A specification example would be lumens per square foot, or reflectivity of surfaces and these are the basis for Performance Specifications at present.

In specifying Activities, we use as measures concepts like amount of user-error permitted, or visual distraction, and we accept those solutions which will permit the USER to achieve his desired level of performance at that activity. A specification example would be percent of error in scanning dials and is relatively unused as a specification procedure other than in newer Human Factors work. This method specifies the Performance of the User.

In specifying Objectives, we would like to use as measures concepts like Productivity, Happiness and Personnel Stability and would accept those solutions which lead to the achievement of these objectives. A specification example would be comfort, privacy, communality. This procedure is, as far as we can ascertain, not used at all at present because of the lack of units of measure.

The concept of Environmental Characteristics is currently the useful one. While implying specific Objectives and Activities, Environmental

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[1] I am indebted to Dr. Thomas Markus at the University of Strathclyde in Scotland for his insights into these issues.

Characteristics are the characteristics which the environment must supply in order for the human user to perform the Activity. These are always in performance terms.

For example, if we were designing a space which contains reading and writing as its primary activities (perhaps a library reading room), one of the critical Environmental Characteristics is adequate illumination. Notice we are not saying we need lighting fixtures, but illumination. There are many solutions to the need for illumination, which includes lighting fixtures as well as windows, illuminated texts, candles, or some unknown device. All are acceptable as long as the desired Environmental Characteristic is supplied.

4. Levels of Application

Let us try to describe how the notion of Hardware, Environmental Characteristics, Activities and Objectives are applied, or might be applied and some problems of application.

4.1 Performance Specifications for Hardware Solutions

It is possible to develop Performance Specifications for hardware solutions. They are not usually user-based, but based upon the known capability of manufacturers to produce hardware with specific capabilities. The most common use is the Product Standard whereby standards of performance and also size, joinery, shape, finish and other prescriptive criteria are used to set the standard for an industry's products. The present products' performances are abstracted, codified and standardized. It is essentially a "dead-end" process in terms of innovation, because the model for performance is not some need but some existing solution.

4.2 Performance Specifications for Environmental Characteristics

These are normally based on users needs (objectives leading to activities leading to the environmental characteristics needed by the user) and form the bulk of performance based procurement in the past decade. Schools have been procured in the states of California, Florida, Georgia, Indiana and in Toronto and Montreal in Canada. Federal Office Buildings will be procured in at least three cities on this basis.

There have been a number of different Performance Specifications developed for Environmental Characteristics, but all have been organized by building subsystems. This has been the case since 1963, when the SCSD Performance Specification was organized into 4 subsystems categories of Structure/Heating, Ventilating and Cooling/Lighting-Ceiling/Interior Partitions. The SEF Performance Specification in Toronto has fragmented the specification into 10 categories but its general organization is by building subsystems.

The procedure[1] used in developing performance specifications has been as follows:

a. A set of Environmental Characteristics is described. These are essentially based on our experience (gathered direct from users or from experts) with the basic needs of users for many building types.

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[1] This procedure was developed by the author while at the National Bureau of Standards and it is believed to have been (either explicitly or implicitly) the procedure used for all user based performance specifications.

b. A set of Building Subsystems is described. These are essentially based on our experience with the functioning of buildings.

c. The Environmental Characteristics are mapped against the Building Subsystems in a Matrix. (A matrix of Environmental Characteristics and Building Subsystems developed by our research group is appended.)

d. Information is developed for each intercept in the matrix which describes the response which each subsystem must have to the desired Environmental Characteristic. Each intercept contains the three kinds of information necessary to understand, measure and test the presence of the Environmental Characteristic -- Requirements, Criteria and Tests.

e. The subsystems portion of the Performance Specification is then organized "vertically" -- that is, by subsystem -- under such headings as "Space Dividers", "Security Systems", "Structure", etc. It is clear, then, that the performance information is developed "horizontally" for each Environmental Characteristic but organized as a procurement document by Building Subsystems.

f. The steps from 1 to 5 are for developing the Performance Specifications for the total system and subsystems. It is not yet a complete document. The complete Performance Specification for design and procurement must contain at least the following:

    1.) Information for bidders/a general description of bidding procedures, technology, expectations, phasing, pre-bid conferences, schedules,

    2.) General Conditions for both Subsystem Development and Construction Requirements,

    3.) Performance Specifications for total System and Subsystems, and

    4.) Bidding or Pricing information.

Although this is a procedure now widely used, there remain several problems with developing performance specifications:

a. By using known subsystems as the method of organizing the specification, we tend to preclude some very basic innovations. A clear example would be for the Activity of bathing and the (normally) attendant Subsystems of plumbing and sanitary fixtures. Both Buckminster Fuller and John Eberhard have demonstrated the feasibility of waterless bathing -- one using a fine mist under pressure and the other using a spray of fine talcum powder. Although neither has been produced, a true performance specification would permit them. Yet all our present performance specifications assume that cleaning the body uses water, plumbing and sanitary fixtures.

b. Performance Specifications deal primarily with the physiological requirements of man. Few, if any, incorporate information about man's sociological and psychological requirements. The ability to do so, and thus, the solution to this problem, rests with the behavioral sciences. But so far they have not produced information of sufficient explicitness to be used in Performance Specifications.

c. Performance specifications have not been organized by Activity -- yet we only experience environmental constraints while performing specific Activities necessary to achieve Objectives -- and, probably do not take into account all of the Activities to which a space must respond with support in the form of appropriate Environmental Characteristics.

4.3 Performance Specifications for Activities

Some of the problems discussed previously may be solved if Performance Specifications are developed for Activities rather than Subsystems. The organizing principle would be to focus on the Activity, for example, of "sleeping" instead of the subsystems which comprise "Bedrooms".

While this notion is far from fully formed, an obvious problem emerges. The building industry is still entirely hardware oriented and could not respond with ease (if at all) to such an organizing principle for a procurement mechanism. Fundamental changes in roles, responsibilities and research would be a necessary prerequisite to such a sophisticated development.

4.4 Performance Specifications for Objectives

The only analogy to such a performance specification is the Planning, Programming, Budgeting Systems (PPBS) used to monitor large scale Governmental Programs. We do not see such a technology transfer into Performance Specifications in this decade.

Since it appears that the last 2 levels of Performance Specifications will not be developed in the near future, in what directions will the state-of-the-art of Performance Specifications move? We would like to offer some speculations and suggestions. For clarity, let us offer certain definitions before the speculations and suggestions:

> A FIRST-GENERATION PERFORMANCE SPECIFICATION is one which develops, elicits or assembles information from users or for users in terms of their performance needs in buildings. It organizes this information in such a way so it may be used as a procurement document to which industry may respond.
>
> A BUILDING SYSTEM is a kit of building parts with sets of rules for their assembly into total operating systems to yield some desired level of performance for some specified time period.
>
> A FIRST-GENERATION BUILDING SYSTEM is a building system which is the first response to a performance specification. It normally involves research and development of a substantial nature by the manufacturers involved.
>
> A SECOND-GENERATION BUILDING SYSTEM is a first generation building system which, through successful application elsewhere, is reused for other projects as is, or slightly modified. It becomes an "off-the-shelf" building system. Fully open systems, developed through first generation performance specifications (like SEF in Toronto), have high promise as second generation systems.

Our suggestion and speculation is that we may now be ready for

SECOND-GENERATION PERFORMANCE SPECIFICATIONS

which might be used to procure:

(A) THIRD-GENERATION BUILDING SYSTEMS

and/or:

(B) FIRST-GENERATION INFRASTRUCTURE SYSTEMS

To procure (A) third-generation building systems, a second-generation performance specification might have some of the following qualities:

a. Attempts to procure substantively higher levels of performance. This implies a research and analysis emphasis on the user's psychological and social needs.

b. Attempts to further develop "vertical open systems" -- by this we mean an open system for a specific building type (like Toronto's SEF matrix bid and compatible subsystems).

c. Attempts to develop "horizontal open systems" -- by this we mean open systems which cut across many building types.

d. Attempts to procure satisfactory cost performance over time by development of first cost/life cost bidding formulas.

e. Attempts to use units of bid which are themselves performance oriented, rather than "thing" oriented.

To procure (B) first-generation infrastructure systems, a performance specification would concern itself with the ecology of buildings or groups of buildings. It would attempt to procure performance-oriented, ecologically sound

a. waste management systems
b. total energy systems for energy management
c. water supply and waste systems
d. anti-pollution systems

In conclusion, we intend this description of present and possible future procedures for developing Performance Specifications to be an attempt to organize some state-of-the-art thinking to enable research in this complex but extremely worthwhile area to continue, to grow and to include some new issues critical to the way we think about, design and procure our physical environments.

BUILDING SUB-SYSTEMS / ENVIRONMENTAL CHARACTERISTICS	Usable Space	HVAC	Utilities	Finished Floor	Finished Ceiling	Luminaires	Space Dividers	Exterior Walls	Plumbing	Sanitary Fixtures	Food Services	Cleaning Systems	Energy Source	Energy Systems	Transportation Systems	Roofs	Windows	Doors	Security Systems	Sealant Systems	Communication Systems	Materials Handling	Waste Removal
Conditioned Air																							
Illumination																							
Acoustics																							
Stability																							
Durability																							
Reliability																							
Health																							
Safety																							
Activity Support																							
Maintainability																							
Esthetics																							
Waste Management																							
Potable Water																							
Food Handling																							
Communication																							
Adaptability																							
Accessibility																							
Azotic Qualities																							

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A Consistent Basis for Functional and Ultimate Criteria

R. N. Wright[1] and A. H.-S. Ang[2]

Objectives in the process of building include minimization of cost as well as performance in meeting functional requirements and safety with respect to property loss or personal injury. The performance concept contributes to these objectives by expressing performance requirements in a manner allowing fair competition among available solution schemes. This paper discusses the formulation of functional and ultimate criteria for structural performance using rational consideration of uncertainties in the information available for decision making.

Functional requirements define limit states of serviceability which are independent of solution scheme. Requirements for safety, however, relate to ultimate limit states which differ in mechanisms and consequences for different structural schemes. This paper shows that performance requirements for safety can be expressed in a scheme-independent manner by accounting for the scheme-dependence of ultimate limit states with reliability-based criteria.

Total performance is described by the expected loss which includes expected initial costs and probable costs of occurrence of functional and ultimate limit states. This formulation guides the expression of performance requirements in ultimate limit states as scheme-independent prescriptions of required reliability. Both statistically defined and statistically undefined uncertainties are accounted for. The fail-safe concept provides very high reliability against catastrophic ultimate limit states.

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[2] Professor of Civil Engineering, University of Illinois, Urbana, Illinois.

Les objectifs dans la construction comprennent le degré de satisfaction des exigences fonctionnelles et de sécurité par rapport aux pertes de propriété et de vie aussi bien que par rapport à la minimisation du coût. L'objectif de la notion de performance consiste à exprimer les exigences afin de permettre la sélection de la meilleure des solutions possibles. Cette communication discute la formulation de critères fonctionnels et ultimes tenant compte au moment de la décision des incertitudes dans l'information disponible.

L'état fonctionnel et l'état limite extrême doivent être tous deux considérés. A partir de la perte prévisible, les états fonctionnels limites impliquent des coûts de dommages indépendants du schéma général et peuvent être forumulés directement selon des critères de performance alors que les limitations ultimes réclament des critères qui soient spécifiquement adaptés à ce schéma. Les formulations excluant l'échec sont essentielles afin de réduire les pertes résultant d'états limites catastrophiques.

Les critères fonctionnels et ultimes peuvent être formulés à partir d'un risque ou d'une mesure de fiabilité. Ceci est nécessaire pour déterminer les pertes attendues et fournir en outre une base conséquente et logique pour l'évaluation des facteurs incertains et de leurs effets sur la conception. Ainsi la performance requise est exprimée comme étant une prescription d'exigences de fiabilité indépendantes du schéma général pour les états limites ultimes.

Key words: Building criteria; design; optimization; reliability; safety; serviceability; structures.

1. Introduction

Structural design is a process involving the conception of the solution scheme and the determination of proportions which assure serviceability and safety. The objective of the design process is to achieve an optimal design with consideration of: function in the intended service, salvage at the end of useful life, and costs for design, initial construction, operation, maintenance, and failures. Designers normally consider all these aspects, formally or informally, in their decision making process. However, the ability to achieve optimal proportions for one particular scheme, or to determine which is preferable among two or more competitive schemes, requires the expression of different costs and values in comparable terms for tradeoffs of qualities.

The objective of the PERFORMANCE CONCEPT is to express desired qualities in a manner independent of solution scheme. This assists in identification of the best scheme among those offered and allows innovative solution schemes to be compared rationally with those of well-established technology. This paper discusses approaches to the formulation of performance criteria for structural serviceability and safety. The treatment of serviceability and safety requirements in formal structural optimization is a related problem area. Both statistically-defined objective uncertainties, and statistically-undefined subjective uncertainties are accounted for in the procedures suggested for formulation of performance criteria.

A limit state denotes incipient unsatisfactory behavior in a specific mode, such as disturbing floor vibrations or punching shear in a slab around a column. The development and the advantages of the concept of limit states are reviewed by Allen [1][3]. A criterion which expresses a desired quality may apply to more than one limit state. However, it is important that each applicable limit state be considered explicitly in design or review of a design. Explicit consideration assures that the actual behavior of the structure receives attention and helps to avoid dangerous or wasteful misinterpretations of criteria. For example, the criterion $F_a \leq .6F_y$, holding tensile stress to six-tenths yield stress, should be considered a criterion for the limit state of yield in tension. It should not be used alone for tensile stress in members composed of metal with a ratio near to one of tensile to yield strength because it would not provide adequate safety with respect to rupture. If limit states of yield and rupture are viewed separately neither is likely to be overlooked. Similarly, a criterion intended to prevent plaster cracking might be considered a criterion for floor deflection and may permit uncomfortable vibrations of novel structural systems.

Functional limit states describe unserviceable behavior which does not involve degradation of the quality of the structure. For instance, excessive sound transmittal through a wall means that the occupants of one side are occasionally disturbed by activities on the other. However, the ability of the wall to attenuate sound or to perform any other function is not altered by the occurrence of this limit state. Performance criteria can be related directly to functional limit states. In terms used by Eberhard [2], the performance criterion expresses the desired attribute which is itself a direct expression of the functional limit state. The present paper treats objective and subjective uncertainties in the driving effect (loading) and the resistance in expressing performance criteria for functional limit states.

Ultimate limit states describe behavior which involves degradation of the system and accompanying loss of serviceability, property, health, or life. A distinction is intended between unserviceable behavior in a functional limit state and loss of serviceability in an ultimate limit state. Perceptible floor vibrations leave the floor unchanged after the excitation; yielding of the floor (noticeable permanent sagging) leaves it less serviceable until repairs are made. Ultimate limit states are scheme dependent, for instance, a concrete slab floor possesses modes of failure different from those of a steel deck and joist floor. This paper discusses approaches to the rational application of scheme-independent, performance criteria to scheme-dependent ultimate limit states, and the use of knowledge of objective and subjective uncertainties in quantitative expression of the criteria.

2. Total Cost Measure of Performance

A single measure of performance is conceptually adequate for definition of the best among a number of competitive structural solutions. This measure may serve as the objective function for unconstrained optimum design or may specify the minimal performance to be accepted. It is the expected total cost

$$C = I + \Sigma_f p_f F_f + \Sigma_u p_u F_u \qquad (1)$$

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[3] Figures in brackets indicate the literature references at end of this paper.

where, I denotes the expected value of the initial cost, p_f the probability of occurence of a functional limit state, F_f the corresponding cost of an occurrence, Σ_f summation over all functional limit states, p_u probability of occurrence of an ultimate limit state, F_u the corresponding cost of such occurrence, and Σ_u summation over all ultimate limit states. Ravindra and Lind [3] and Rosenblueth and Esteva [4] have used essentially this formulation.

The initial cost may include all variable costs which accrue prior to the use of the structure, and can include present worth of operating, maintenance, and removal costs. These formulations are familiar from engineering economics and receive no further attention.

For a functional limit state, p_f and F_f do not reflect the probability and cost of a single occurrence during the service life. For instance, in design of the World Trade Center, Feld [5], perceptible wind-induced vibrations are expected to occur 12 times per year. The loss is a loss of functionality so F_f can represent the cost of the limit state occurring continuously, and p_f the probability of occurrence considering both spatial and temporal distribution.

For an ultimate limit state, p_u and F_u must account for the many locations in which, and the many loadings for which, that specific limit state can occur. For instance, yielding of a beam may involve any one of many similar beams grouped by material properties, cross section dimensions, and length for essentially the same cost of failure F_u, as well as many possible mechanisms for each beam.

2.1 Direct Application in Design

The total expected cost criterion could be applied directly as the objective function for an optimum design procedure using material properties and member proportions as design variables. Input information would include probabilistic descriptions of the attributes dependent on the design variables. Thus, probabilities of failure would be defined implicitly; unconstrained optimization procedures, as described by Wilde and Beightler [6], would lead to an optimal solution.

This approach merits investigation and may become practical when simple approaches to evaluation of the product pF for the various limit states are shown to be reliable. One particularly challenging requirement is expression of dependence among limit states which exists when occurrence of one affects the load or resistance for another. The dependence is mathematically inconvenient, but has great practical value. A catastrophic limit state leading to sudden, expensive failure, such as punching shear of a slab around a column, Engineering News Record [7], can be avoided if a more benign limit state, such as large deflection of the slab due to flexural yielding, gives warning of overload. Formulations providing for this Fail-Safe behavior are discussed further in the following development.

2.2 Guide in Formulation of Criteria

Much research is required before direct application of the total cost concept is practicable in design, but the concept is immediately applicable as a guide for the rational selection of coefficients of criteria such as load factors and factors of safety. Ravindra and Lind [3] have explored the use of such coefficients of criteria as variables in design of a specification. They suggest minimization of total cost over the expected range of applications to arrive at optimal coefficients.

The traditional approach to establishing design criteria uses the best available estimates of I, p, and F from Eq. (1) for guidance. This procedure, expressed formally, begins with a current state for all criteria, and for the criterion in question considers the marginal value of a change in coefficient ΔC as $\Delta I + \Delta(pF)$. These terms usually have opposite signs; the optimal C, by the Kuhn-Tucker conditions, Wilde and Beightler [6], occurs when $\Delta I + \Delta(pF)$ is zero for a small ΔC. This is a somewhat formal statement of the engineering judgement "a higher load factor would cost more than it is worth." It is interesting that the traditional engineering approach, followed carefully, is an iterative approach to optimization of a specification. The point emphasized is that information on I, p, and F is essential to the validity of either approach. Judgements must be made, but they should be based on the best available information.

3. Extended Reliability Bases for Criteria

The information available to the designer or specification writer on cost, value, and behavior of structures always will contain objective and subjective uncertainties; that is, statistical variabilities and uncertainties of predictions arising from lack of adequate statistical information. This section describes a rational approach for accounting for these uncertainties in the development and implementation of criteria leading toward performance at arbitrary levels or minimum total cost.

3.1 Reliability in Functional Limit States

The formulation of required reliability in a functional limit state is straightfoward because the cost of occurrence F_f is scheme-independent and the required probability of failure p_f is on the order of 10^{-3}. The scheme-independence simplifies specification of p_f, which may be constant for all designs or may be varied for minimum total cost. The acceptability of a relatively large p places it in a distribution insensitive range, Ang and Amin [8]. Thus knowledge of the means and variances of the driving and resisting effects are sufficient to evaluate the required probability. The probability of an occurrence is expressed by

$$p_f = P(R < NS) \qquad (2)$$

where R and S are random variables denoting the resisting and driving effects, and N is a random variable, of mean value equal to unity, which expresses statistically the degree of confidence in the knowledge of R and S.

Since there is limited sensitivity to distribution for the range of probabilities required, the lognormal distribution may be assumed for R, S, and N in Eq. (2). On this basis Ang and Ellingwood [9] express the required central factor of safety, $\gamma = \bar{R}/\bar{S}$, as

$$\gamma = \frac{\bar{R}}{\bar{S}} = \exp\left[\Phi^{-1}(1 - p_f)\sqrt{\delta_R^2 + \delta_S^2 + \Delta^2}\right] \qquad (3)$$

where δ_R, δ_S, and Δ are, respectively, the coefficients of variation of R, S, and N, and $\phi^{-1}(1 - p_f)$ is the value of the standard normal variate corresponding to a cumulative probability of $(1 - p_f)$.

3.2 Reliability in Ultimate Limit States

The formulation of required reliability is complicated for an ultimate limit state because both the existence of the limit state and its cost of occurrence, F_u, depend upon the solution scheme and the permitted probability of occurrence is on the order of 10^{-6}. The former complication requires special attention in the evaluation of p_u. The extremely small value of p_u places it in a distribution sensitive range, requiring, therefore, precise knowledge of these distributions which are, however, most difficult to obtain in practice. This difficulty has been studied by Ang and his colleagues for several years; Ang and Ellingwood [9] provide a useful formulation of reliability for ultimate limit states.

The distribution sensitivity can be avoided if an alternative measure of risk is adopted; namely,

$$p_u = P(R \leq \nu S)\, P(N \geq h\nu) \tag{4}$$

where ν is a specific value of N, and h is a parameter introduced to make this alternative risk equal to $P(R \leq NS)$ under certain conditions [9].

On the basis of Eq. (4), designs are obtained for a specified risk $p_u = p_o p_s$ from

$$p_o = P\,(R \leq \nu S) \tag{5}$$

in which ν is obtained from $p_s = P(N \geq h\nu)$, Ang and Ellingwood [9],

$$\nu = \exp\left[\sqrt{\delta^2 + \Delta^2}\;\phi^{-1}(1 - p_u) - \delta\phi^{-1}(1 - p_o)\right] \tag{6}$$

where $\delta = \sqrt{\delta_R^2 + \delta_S^2}$, $p_o = (p_u)^{\frac{\Delta}{\delta+\Delta}}$, and $p_s = (p_u)^{\frac{\Delta}{\delta+\Delta}}$

Then, the required central factor of safety may be derived from Eq. (5); for lognormal R and S this yields

$$\gamma = \frac{\bar{R}}{\bar{S}} = \exp\left[\phi^{-1}(1-p_u)\;\sqrt{\delta^2 + \Delta^2}\right] \tag{7}$$

3.3 Fail-Safe Concept

Dependencies of ultimate limit states require attention because the probability of an extreme loading in a catastrophic limit state is reduced sharply if the occurrence of a more benign limit state is likely at a smaller load. For instance, the probability of shear failure in a reinforced concrete beam, and perhaps also the initial cost and expected costs of failure, can be reduced by removing some flexural reinforcement to give more certain warning of overload by occurrence of sagging. This fail-safe approach can be formulated in the manner described above if effects of other limit states are considered in the frequency distribution for the loading S. Translation into prescriptive criteria may require both lower and upper bounds on resistance, e.g. $\bar{R} > \gamma\bar{S}$, $\bar{R} < \omega\bar{S}$ where γ and ω respectively denote minimum and maximum central factors of safety.

4. Implementation as Practical Performance Criteria

The total expected cost criterion of Eq. (1) cannot at present be applied directly in most design situations. The present uncertainties in knowledge of costs and in probabilities of occurrences of limit states as functions of design variables are too great to assure real gains from attempts to adjust design variables to minimize total cost. These uncertainties justify present use of specific criteria for performance in individual limit states. Even as knowledge improves, it will remain essential to apply specific criteria as a final check to guard against mistakes, such as incorrect input, which would be difficult to detect using only the total cost criterion. A practical formulation of performance criteria can meet this need and remain consistent with the objective of rational comparison of alternative schemes.

A scheme-independent procedure for design for minimum total cost is possible only by direct application of Eq. (1). However, the initial costs provide a consistent basis for selection of the best alternative if the probabilities of occurrence of applicable limit states are prescribed in a manner leading to comparable expected losses in all solution schemes. The severity of ultimate limit states is in proportion to the cost of occurrence F. The central factor of safety γ for each limit state may be specified to hold the expected cost of its occurrence to a prescribed level. This expected cost of occurrence can be held essentially constant for all limit states of all schemes by using the classification described below.

The major classes of ultimate limit states in structures are: (1) yielding, which causes permanent deformation after removal of the loading, (2) instability which involves permanent deformation increasing under constant or decreasing loading, and (3) rupture which causes abrupt loss of all load carrying capacity of an element. On a basis of unit affected areas, the three classes of ultimate limit states involve losses in increasing proportions such as 1:10:100 since yielding rarely involves loss of supported property or life, risk of these losses is greater with instability, and rupture involves greatest risk. The proportions cited are approximate, and should be carefully revised in light of the specific structural function.

The cost of occurrence is well defined by the cost per unit area times the area affected. On this basis, and for uncertainties expressed by normal distribution, occurrence of yielding affecting 10 m^2 might be assigned $p_u = 10^{-4}$ for a relative expected cost $p_u F_u$ of $10^{-4} x 1 x 10 = 10^{-3}$. For consistency, occurrence of rupture affecting 100 m^2 would be assigned $p_u = 10^{-7}$ for the same relative expected cost, $10^{-7} x 100 x 100 = 10^{-3}$.

The application of the performance concept to ultimate limit states described by Yokel and Somes [10] has used a scheme-independent description of design loading, well in excess of the central loading $\bar{S}$, and required approximately 95 percent probability that the supplied resistance exceed the specified load. Their approach accounts for uncertainty of loading and resistance in a manner consistent with an assigned probability of occurrence. Rosenblueth and Esteva [4] consider assigned probabilities of failure in various modes to be a second stage in evolution of building codes. The formulation described here goes beyond the cited work to account for wide variations in cost of occurrence of different limit states, the dependence of limit states in relations of load to resistance, and can provide consistent probabilities of occurrence of the design loading combinations.

5. Summary and Conclusions

The performance concept for formulation of structural design criteria is attractive because it provides a quantitative basis for selection of the best among alternative solution schemes and permits fair competition between well-established and innovative technologies. The total expected cost criterion is presented as the objective function for optimization of performance, and employed as a basis for evaluation of the consistency of alternative expressions of performance criteria. Distinctions between costs of failure, and objective and subjective uncertainties in loading and resistance are shown to play an important part in evaluation of performance.

Functional limit states are seen to be well adapted to performance criteria because the existence of the limit state and the cost of its occurrence are scheme-independent. A performance criterion may be developed directly for each functional limit state to provide a specified maximum probability of occurrence. Rational account is achieved automatically for the greater uncertainties of resistance associated with innovative solution schemes.

Ultimate limit states are dependent on solution scheme in both their existence and consequences of occurrence, and require explicit consideration in a rational process of design. A classification of ultimate limit states in accordance with the consequences of their occurrence provides a rational basis for expressing performance criteria as scheme-independent, consequence-dependent, specified maximum probabilities of occurrence. The probability of occurrence should reflect objective and subjective uncertainties in loading and resistance, and dependence of limit states. Dependence of limit states permits use of a fail-safe approach to economical assurance of very low probabilities of occurrence of catastrophic limit states.

6. References

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Performance Concept and The System Approach - Some Comments

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The paper will comment on two main approaches for use of the performance concept: behaviour in use and output of a process. The system approach, applying inter alia the performance concept, can be used in different stages of the building process, particularly for description of the wanted result, the final system. The author tries to give examples of applications on different product levels. The ER Quality description system is one example. The author comments on the help given by classification in the applications and the relations between classification categories, levels and classification.

L'auteur discute deux méthodes principales pour l'utilisation du concept de performance: comportement durant l'usage et rendement d'un processus. La méthode des systèmes qui applique, entre autres, le concept de performance peut être utilisée à différentes phases du processus de construction, particulièrement pour la description du résultat désiré, le système final. L'auteur essaie de donner des exemples d'application à différents niveaux de production. Le système de description de qualité ER en est un exemple. L'auteur discute l'aide fournie par la classification dans les applications et les relations entre catégories de classification, entre niveaux et classification.

Key words: Building; design process; ER-system; performance; performance concept; quality description; system approach.

1. The performance concept

The performance concept has been given different applications. Perhaps one could state that there are two main approaches for the definition and for the use of the performance concept. They are:

i) Behaviour in use, which means the behaviour of a thing, (e.g. a building, building element, building component etc.) in its environment under its exposure to different agents.

ii) The output of a process (transformation by activities or by function) - a kind of performance. In this interpretation one can go back to the original expressions, to perform an activity or to perform a function. The function of a building is related to the functions of the parts of the building. The function concept is related to the system concept. The relation between system and function can be expressed by help of a model, which inter alia makes it possible to get the performance of the whole(system performance) as a result of the performance of the parts (subsystem performance).

The mentioned approaches represent two sides of the same coin. It seems, however, useful to realize that some people use the first mentioned approach to the performance concept while other people use the second approach.

2. System thinking

If one treats performance as a general concept related to system thinking as an output from a 'fundamental block' in a system model, one can state that it is applicable at all system levels (from material upwards and from building downwards). One can also use the performance concept for quality planning and quality management in a process, e.g. the building process. A process means the transformation from one system to another. One can require a performance from each transformation and get a performance supplied and then one can control if the supplied performance is within the allowed tolerances of the required performance. The required performance can be expressed in functional terms (as in performance specifications) as well as in activities (as in job specifications), in the latter case it is often combined with specifications of resources (e.g. materials). The linking of the performance thinking to process models, to assessment models and to cost/utility models seems to be a fruitful approach, but it needs a hard discipline in the use of the concept and the term performance. Maybe a synonymic to performance would be practical to introduce in the future for these disciplined applications.

One has not to forget that in the definitions of performance used by the National Bureau of Standards and also used as a basis within the CIB Working Commission W60 (that the performance concept is an organized procedure or framework within which it is possible to state the desired attributes of a material, component or system in order to fulfil the requirements of the intended use without regard to the specific means to be employed in achieving the result) the definition mentions an 'organized procedure or framework', which refers to systems thinking.

A process can be divided into systems and subsystems. A fundamental property(acc. to Ashby)[1] of systems is that they can be steered or controlled by application of cybernetics, which gives methods for studies and control of complex systems. Hereby the feed-back function from a later stage in a process to an earlier one for corrections is important and the performance thinking can contribute in the development of simplified tools for feed-back information.

The general words properties and/or attributes, have often been considered as related only to a thing as such and not to a thing interacting with its environment. Such interpretations have caused unnecessary barriers between different approaches in building legislation, research and information. The system thinking here can help a mutual understanding if one treats the performance properties as output from a black box of which the interior mechanism is of no interest (close to the NBS-definition mentioned above) and the other properties as those which are either of no interest for the output of the box or which are known more in detail (parts of the interior mechanism).

One cannot speak about properties and relations as such but have to refer them to systems and their changes (Bunge). Bunge applies the term concrete systems for physical things, distinguishing them from conceptual systems (theories).

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[1] See literature references at the end of paper.

The interaction between environment and the concrete system within the actual universe of discourse (reference set) is one of the bases for the application of the performance concept. Similar models could be applied for animal behaviour as for technical machines behaviour. This means that the following pairs are analogues:

stimulus from environment → response of system (reaction of organization) → effect on environment
action → reaction → effect
input → output

In this context one has to regard physical parameters as well as non-physical parameters and also measurable and non-measurable properties; sometimes the terms 'soft data' and 'hard data' are used. If one, by help of systems thinking, tries to get workable models of the 'whole' (acc. to Feibleman and Friend anything is a 'whole' which operates in quasi-independence of its environment. 'Wholes' are not a level for analysis but that from which analysis starts. Parts are the first level of analysis.). There is a better chance with help of systems thinking that all relevant parameters are taken into account, measurable as well as non-measurable. In system engineering one has to develop principles to handle uncertainties. Evaluation technique has to consider not only testing but also classification and ordering and the whole range of evaluation techniques. System thinking gives an opportunity to consider and handle all relevant factors which constitute the total output, the performance. Regarding properties of a concrete system one can divide them into structural and functional properties. (Cf. inter alia Ackoff and Feibleman & Friend).

According to Ackoff the structural properties (referring either to the matter (or material) of which a thing is composed or to its form, or both) are 'essentially deterministic in character' and the functional properties (referring to how a thing or event came into being or what it does or can be used for.

The members of a system are constituents of the system by means of their arrangement within the system (cf. inter alia Angyal). This means inter alia that levels are important and also that relationships exist between arrangements within a system and general categories inter alia applicable for a classification system. Some types of categories, and also an example of general division of levels (figures 1 and 2), are illustrations of this. Higher levels can be said to be based on lower levels. Categories and levels can be used to characterize subsystems or groupings of operational character, e.g. by classification, and thereby help to demonstrate the relations.

The examples given show that it could be useful to analyze the character of the actual level before placing it into a hierarchy of levels for which the rule is valid that the performance (the output of transformation blocks) is transferable from one level to another.

3. The structuring of information by help of classification

If we regard models based on the block diagramme principle, the block diagramme can be used to break down a problem into smaller parts of the problem, and then synthesized to a new integration, whereby one can use a catalogue of blocks already analysed. This means inter alia a list of variables. In order to facilitate the applications, such lists could be structured in an unified way.

Also when comparing and assessing different alternatives, which are elaborated in order to solve a problem, it is urgent to select which parameters are relevant for assessment and how the properties are measured (evaluated). One needs check lists with attached information about principles for assessment. Also in these cases, a structuring of the different catalogues is useful for the work and for the communication of the work results. Some examples are mentioned below:

The international SfB System administrated by CIB (CIB Working Commission WC 58) has at present three classification categories: building elements, constructions, and resources which cover the objects below the level of building.

The CIB Master List of properties developed internationally within CIB (CIB Working Commission WC 31) gives the framework for the unified structuring of information on 'properties' (properties in a wide sense). The list is in revision and will be presented as a basic list together with a set of applied lists for different levels. The structure of the revised basic list is demonstrated in figure 3. The Master List can be used as a check list in the selection of relevant parameters, as an organized framework for unified information on technical solutions available in a market, the formulation of requirements from clients, and in regulations.

The ER-system is another example. See below.

4. The ER-system

The Swedish ER-system[+)] (now a Scandinavian system) has been developed as a system for structured and controlled information on technical solutions in the building industry, giving information not only on physical characteristics (structural properties) of products of different levels but also on those properties which are of interest for assessment of behaviour in use (functional properties). Relevant parameters are selected and evaluation techniques are discussed and decided by groups of experts (users and producers). Thereafter the different products are described and the ER-documents are published in cooperation between the producers, the ER Council and the Swedish Building Catalogue (Svensk Byggkatalog, produced by the Swedish Building Information and Documentation Centre). In this connection the levels of property values (level of performance) are given. The ER-documents give no requirements but give organized and unbiased information which helps those who solve problems and formulate requirements, and those who make the decisions about technical solutions. The so-called ER-surveys give a basis for formulating requirements in a project and the ER-sheets give data about individual products from different manufacturers.

Data (unevaluated messages) are necessary as a basis for decisions about building products and technical solutions with regard to the needs and requirements which exist in a certain situation and give the basis for decision to be transferred further in an actual project.

The ER-system is briefly explained in figures 4 and 5.

The ER-work has started at the component and materials level and is now moving 'upwards' The whole work done up to now within the ER-system is necessary, because the whole (the building element or the building) can be regarded as a system consisting of its parts, and those parts must in all cases be analyzed.

In the ER-work the stimulation of development of information about 'behavior in use' was one of the basic thoughts already considered at the beginning of the work about ten years ago. One has to consider that there is a need to express requirements and to know properties at higher product levels incl. sub-elements. In the ER-work we have, however, met obstacles due to incomplete knowledge about functions and about higher product levels.

Decisions by building practitioners about commodities are taken in many contexts and by different functions (persons) in different phases of the building process. The problems are solved by help of iterative procedures. The solution of a problem is facilitated inter alia if a generally accessible knowledge is available. by defining the problem and by classification of problem and data. When data about building products (commodities) and other technical

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[+)] The work of The ER Council is supported by The Swedish Council for Building research. ER means Egenskapsredovisning.

solutions are used for decisions,one must consider that one in many contexts is striving to get knowledge about the function of the product with regard to the user. One thereby seeks to evaluate the technical suitability in relation to the economic suitability, sometimes under strict application of value analysis. The user and his adviser are hereby,in principle, not interested in how the solution is developed or in its content.

From interviews amongst building practitioners of different categories one can state that the practitioners' own experiences from earlier problem solutions have a big importance for decisions on new technical solutions. Second hand importance has the use of coordinated, embracable information of type Byggkatalog and ER, containing data which can be compared. One can today state that the practitioners often do not have a practical possibility of applying experiences of their own earlier applied solutions. In those cases where own experiences exist they also need an improved basis for decisions. To that can be added two facts which emphasize the importance of unbiassed quality descriptions and at the same time the importance of performance thinking: i) maintenance costs will increase and the durability will be of more importance; ii) the increasing international trade of building commodities requires increased international coordination.

An important question is what shall be put only into a commodity file, e.g. a card index,or an EDP data file, and thus not be published as a document. One has to consider the necessity to restrict the overload of printed information to the practitioners.

Thereby one must regard how an ER Quality description can be made so that it is short and simple,and at the same time gives information in a way which is fair for the producer. Our first approach has given a solution which has created a certain complexity to the information. It is, however, important to simplify the tool, which is possible if both the producer and the user will accept such simplifications.

The ER Quality descriptions apply the SfB-system and the CIB Master List of properties for the structuring (figure 6) and get help from RILEM work and from joint Scandinavian work on testing methods,as well as from the work in CIB W 60 "Performance concept in building" concerning selection of relevant parameters for building elements and concerning evaluation technique.

5. The application of the same pattern for the classification at all product levels

Lists of variables of interest to ER-work and similar work are relevant for different product levels. If the lists could be structured in the same way through the levels, it would facilitate their application. Meredith introduces the concept of 'modularity' which means the capacity to understand more than one level and gives an opportunity to handle the relation between properties of bodies of different orders of magnitude.

In the revision of CIB Master List of properties 'modules' are applied in order to give a unified structure for the lists on all levels. These 'modules', which are closed and subdivided,or open without subdivisions, have shown themselves to be useful in the creation of the list. It is also a hope that the application of such modules is a useful tool for product development, inter alia the application of the performance concept, as this concept always is related to the total result.

The Master Lists are used for structuring information at the levels: building, building elements, building components and materials,and mechanical systems (services and installations). The lists are intended for use at the design stage, construction stage and usage stage. The lists are intended for structuring information on structural and functional properties as well as those of commercial and economical character. They do not,however,at present cover the interaction between the physical environment and the user more than as an open module without subdivision.

Requirements and properties have to be matched at the same level. A general pattern for such matching is demonstrated in figure 7.

6. Coordination of future development

The application of the performance concept in building has been promoted because of the need for help in product development and the need for description and assessment of new products or new applications. The practical tools for improving the building process by using the systems thinking and performance thinking have to be developed parallel to the application of the performance concept in product development.

The future development of performance thinking within a systems approach to building, and the development of tools for communication and classification in the building process, have in the future to be in close contact with each other in order to facilitate the work in the building process for the building practitioners and in order to create a good relationship between requirements given inter alia in regulations and by clients on one side, and the technical solutions given by the industry on the other.

The performance concept can be used also in formulating requirements on communication tools giving assistance to the building process. The communication process has a high degree of complexity and it seems therefore to be fruitful to apply the performance thinking also on this resource in the process (cf. inter alia papers and discussions concerning Documentation in CIB Congress papers, June 1971).

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Ranganathan	Vickery	Mills	Meredith
Personality	Things, substances, entities	Whole/Thing	Agent
Energy	Their parts	Kinds	Instrument
Matter	Systems of things	Parts	Task
Space	Attributes of things	Materials	Connection/Adjency
Time	Object of action (patient)	Processes	Material
	Relations between things, interactions	Properties	Operation
	Operations on things	Agents	Structure
	Place condition	Operations	Amount
	Time		Property
			Design
			Removal
			Substitute

Fig. 1 Examples of classification categories

Kinds of variables, which together with scientific laws characterize different levels

Physical variables

Biological variables

Pshychological variables

Sociological variables

Laws relating variables belonging to the same level = intra level laws

Laws relating variables belonging to different levels = inter level laws

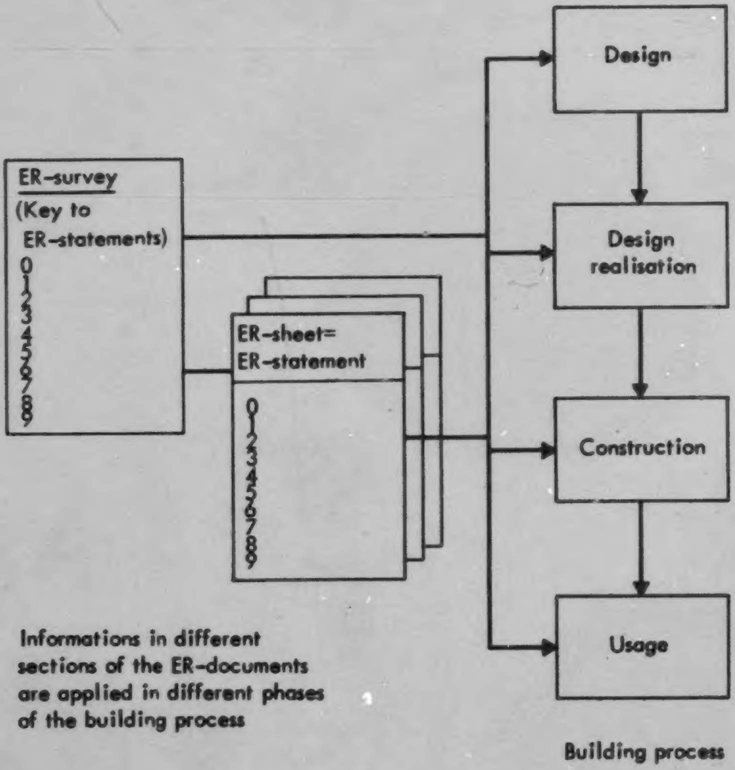
Examples of inter level laws

- Psychological & psychochemical laws
- Socio physical laws
- Socio biological laws
- Biophysical & biochemical laws
- Sociobiophysical laws

Fig. 2 Examples of division of levels (acc. to Bunge)

0 DOCUMENT, key information for indexing
1 IDENTIFICATION, key information
2 DESCRIPTIONS of product including working characteristics
3 ENVIRONMENTAL data
4 CHARACTERISTICS of product relevant to behaviour in use
5 DESIGN, key information
6 Instructions for HANDLING and WORK ON SITE
7 Instructions for OPERATION and MAINTENANCE
8 COMMERCIAL
9 REFERENCES

Fig. 3 Sections of the basic list of the revised CIB Master List for properties.


ER-survey
(Key to ER-statements)
0
1
2
3
4
5
6
7
8
9
ER-sheet=
ER-statement
0
1
2
3
4
5
6
7
8
9
Design
Design realisation
Construction
Usage
Building process

Informations in different sections of the ER-documents are applied in different phases of the building process

Fig 4 ER-documents and the use of them in the building process

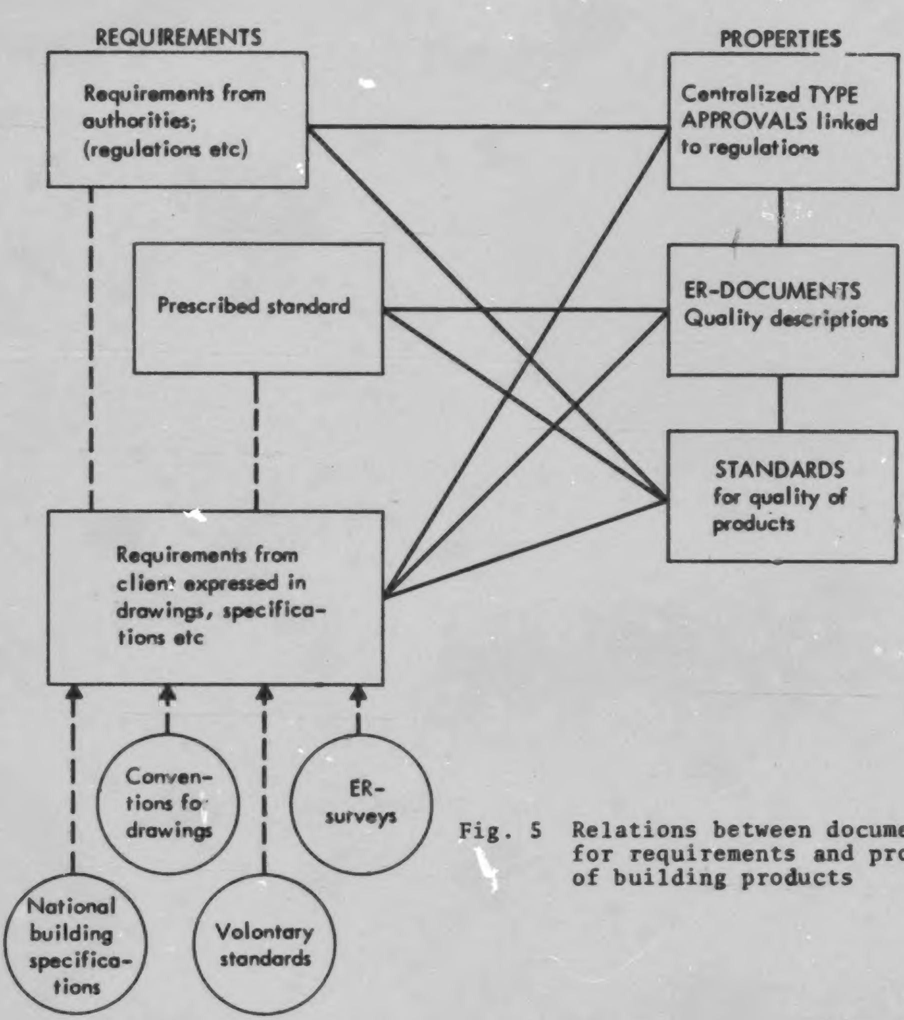

REQUIREMENTS
PROPERTIES
Requirements from authorities; (regulations etc)
Centralized TYPE APPROVALS linked to regulations
Prescribed standard
ER-DOCUMENTS Quality descriptions
STANDARDS for quality of products
Requirements from client expressed in drawings, specifications etc
Conventions for drawings
ER-surveys
National building specifications
Volontary standards

Fig. 5 Relations between documents for requirements and properties of building products

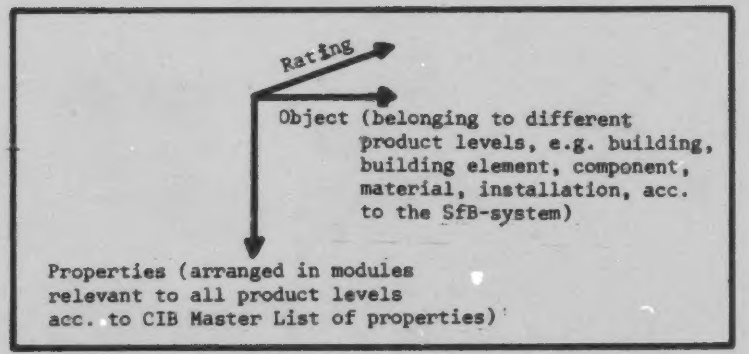

Rating
Object (belonging to different product levels, e.g. building, building element, component, material, installation, acc. to the SfB-system)
Properties (arranged in modules relevant to all product levels acc. to CIB Master List of properties)

Fig. 6 "Coordinates" of the ER-system

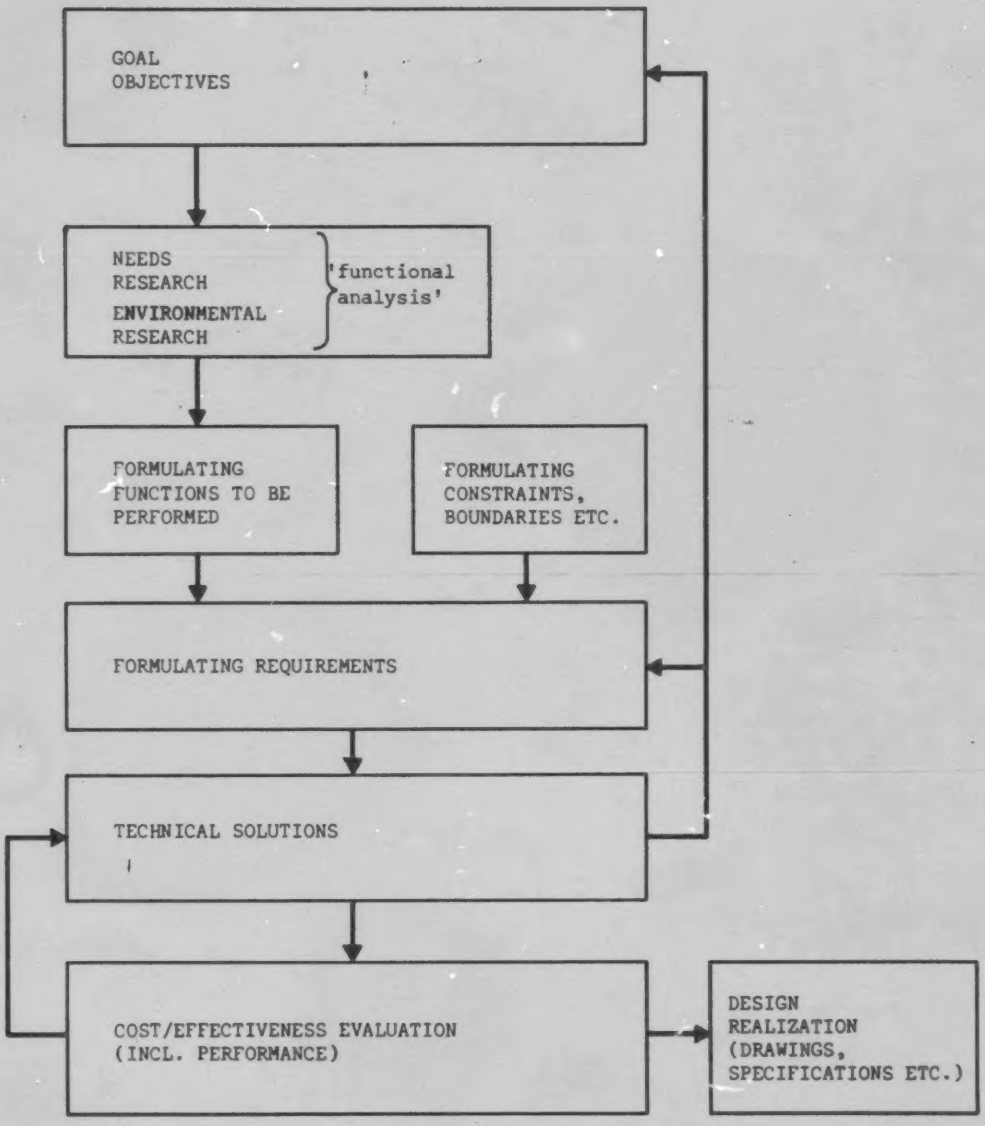

GOAL
OBJECTIVES
NEEDS
RESEARCH
ENVIRONMENTAL
RESEARCH
'functional
analysis'
FORMULATING
FUNCTIONS TO BE
PERFORMED
FORMULATING
CONSTRAINTS,
BOUNDARIES ETC.
FORMULATING REQUIREMENTS
TECHNICAL SOLUTIONS
COST/EFFECTIVENESS EVALUATION
(INCL. PERFORMANCE)
DESIGN
REALIZATION
(DRAWINGS,
SPECIFICATIONS ETC.)

Fig. 7 Model for formulation of requirements and evaluation of technical solutions.

(From I.Karlén: The application of the performance concept in the structuring of information in quality planning (CIB W 31/VII/5).

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The Performance Concept in Building: The Working Application of the Systems Approach to Building

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The paper reviews the meaning of the systems approach to building in its practical context. Attention is drawn to the local factor in building when consideration is given to performance requirements. A characteristic which separates theory from accomplished practice in building. It is suggested that the local factor in building could make the notation of the pure performance approach to building something of a hoax, or at least common and current misconception in the industry. The realities of building performance assessment on major systems programmes are noted and a suggestion is made that the concept of the(pure) Performance Approach or Concept of Building should be discarded. It is recommended that the Performance Judgement Approach or Concept be adopted as a more accurate representation of the daily realities of performance-based building practice.

The paper proposes the establishment of an international Generic Building Classification for the bulk of common building uses. It reviews the apparent divergent meaning of performance specifications as they appear to be finding application in Europe and North America. A proposal is made for the establishment of international sub-system classification models and two examples are given for schools and housing.

The paper concludes with an appeal for a major increase in user requirements research and the development of science-based skill in the building industry. It appeals also for a major rationalization of all skills in the industry in the expectation that with building code rationalization the building industry would then have the comprehensive resources necessary to make the performance concept in building a reality.

La communication passe en revue le sens de la méthode des systèmes dans la construction dans son contexte pratique. On attire l'attention sur le facteur local dans la construction en regard des demandes de performance: une caractéristique qui sépare la théorie de la pratique achevée dans le bâtiment. On suggère que le facteur local dans la construction pourrait faire une attrape de la notion de pure performance comme méthode ou, du moins, mènerait à des malentendus communs et courants dans l'industrie. On note les conditions réelles de la fixation de performance pour la construction s'appliquant aux programmes de systèmes principaux et on propose que le concept de la méthode de pure performance ou concept de construction soit abandonné. On recommande que la méthode d'estimation de performance ou concept soit adoptée comme plus exactement représentative des conditions réelles journalières de la pratique de construction fondée sur la performance.

La communication propose l'établissement d'une Classification Générique internationale du Bâtiment pour la masse des utilisations courantes dans la construction. Elle passe en revue le sens apparemment divergent de spécifications de performance comme elles semblent trouver leur application en Europe et en Amérique du Nord. On propose l'établissement de classification internationale de modèles de sous-systèmes et on donne deux exemples pour écoles et habitations.

La communication conclut par un appel pour une augmentation majeure dans les recherches touchant aux demandes de l'usager et dans le développement de compétence fondée sur la science dans l'industrie du bâtiment. Elle réclame aussi une rationalisation majeure de tous les métiers dans l'industrie, dans l'espoir qu'avec une rationalisation de codes de construction, l'industrie du bâtiment aurait alors les ressources d'ensemble requises pour faire du concept de performance dans la construction une réalité.

Key words: Buildings; design process; performance; performance concept; performance-judgement approach; proposed international generic building classifications; proposed international subsystem classification models; systems approach; user needs.

The systems approach to building is simply a matter of giving balanced consideration to, and committing appropriately balanced resources to, every aspect of a building activity, where an aspect of a project includes its finite and tangible features, as well as its peripheral and intangible qualities.

As such, the systems approach to building gives balanced consideration to every influence bearing on a specific building activity. Under the systems approach, an activity of building is dealt with only in its context as part of a full life process. Building and living are dealt with simultaneously.

The systems approach to building, once identified and named, is the only truly sane way of approaching the provision of the built environment, accepting as it does the responsibility of providing adequate weight to every factor bearing on a specific act of building which can be identified, while at the same time reducing the process of providing that built environment to its simplest operational form. The systems approach to building does not, of course, automatically imply the use of industrialized building systems or indeed any change in the material methods of building. It does imply radical management changes. The systems approach, if fully exploited, does imply a radical rearrangement of building methods, techniques, and management. This view of the systems approach to building suggests the reduction of building from a process involving between twenty and thirty trade categories, depending upon the region under observation, to perhaps 10 sub-systems where each sub-system provides a discrete and major element of a finished building.

The acceptance of the sub-system approach to building in an open systems context, provides a rational basis for the reorganization of the building professions and building trades which is directly derivative from the traditional industrial structure, and also provides the most rational context in which to approach the questions of definition of building elements and performance.

A key aspect of the systems approach to building which might also be called the common-sense approach to building, (and as such is not new) is the establishment of performance requirements. The latter meaning simply: A description of exactly what a building is supposed to do, in whole and in part, in a given functional context. A clear description of how long it is to perform, what must it cost to make and keep up, and what special conditions exist on the job in question to prevent it from being done in the most obvious and straightforward way, where the latter constraint could be called the local factor.

Many theoreticians of the performance technique of defining building requirements make a grave error in ignoring the local factor I have added as part of performance requirements.

In day-to-day practice it is this local factor which separates theory from accomplished practice. This is the customized or intrigue factor in building. The one which makes building radically different from every other social production activity. It is the factor which continuously ensures that accomplished building projects often look like a parody of their original design presentations. The local factor in building is the one which has, and always will, make building the only true expression of any society's values and aspirations at any given time in its history. It is also the one which will prevent the industrialization of building from following the model of automobile, aircraft, or even ship building industrialisation.

The local factor is also the one which makes the entire performance approach to building something of a wildly popular hoax, the best hoax since modular co-ordination, another concept compromised by the local factor. I suppose it is slightly heretical to suggest that we are gathered in conference to nod learnedly over a hoax, but we are perilously close to that state.

The performance concept in building presupposes that we can describe with scientific exactitude what a building or part of a building is to do, and how we propose to measure that performance of the thing before and after delivery and erection. I regret that the majority of persons deriving their livelihood at all levels of the building industry lack sufficient knowledge of building science, the processes of building element manufacture, the cost control, the design and the assembly of buildings and their detailed maintenance and operation, to make the judgements required to use the performance approach to building in its pure form. We need not be too concerned for the moment with our collective ignorance, as the rest of the industrial community have for all practical purposes no knowledge in this area.

All the major building performance-based programmes undertaken to this date in the United States and Canada (and I would suspect Europe also) have gently cheated on the question of performance evaluation. The vast number of unknowns in programmes like the United States Department of Housing & Urban Development's Operation Breakthrough, the Metropolitan Toronto School Board's Study of Educational Facilities (SEF), and the First California School Commission's School Construction Systems Development Project (SCSD), concerning interpretation of performance are settled not be exact measurement but by judgement or fiat. In programmes such as SEF this fiat is exercised by the Technical Director, for Operation Breakthrough this role is performed by the Director and the National Bureau of Standards. Both, I am sure, would be prepared to admit that there is no known practical way of measuring by recorded test procedures a substantial percentage of the performance requirements set out in performance specifications in current use - that is, test procedures which can be used to monitor products or sub-systems during design, production, and erection; that are inexpensive and widely known to the building professions and building officials; and that would not slow down construction operations; which are also sufficiently predictive to avoid the excessive rejection of products already manufactured and erected; and, consequently, avoid job disputes and litigation.

In many ways I feel it would be more realistic, even honest, to discard the notion of the pure performance approach to building specification and evaluation, and substitute the Performance-Judgement approach. I can see no way in the foreseeable future that judgement is going to be replaced by test-based scientific method as the day-to-day practice of the building industry for making choices between alternate ways of building. We are an earthy lot in building; the ways of aerospace don't fit us any better than those of the number pattern theorist, and we do not have the money, time, patience or skill for either way. Subjectivity rather than objectivity, generally, is characteristic of building as it is of the overall life process which building must house and always reflect. In discussing the performance concept hereafter I shall mean the Performance-Judgement approach to building.

Ideally, the performance requirements for generic building types and the sub-systems components of buildings should be established in absolute terms, where a user activity is evaluated within its ideal philosophical climate together with the quantifiable physical descriptions of what a built environment must do to meet the needs of the user's activity in that ideal climate. Performance requirements established in this manner are of little practical value, as they tend to overlook the local factor. They do have an academic use as a research tool for the development of the techniques of user requirement analysis and performance requirement definition. As such, they belong in the university research centre. To be of practical use, they must be re-interpreted by the building profession into the local language of actual projects. From the view point of the systems approach to building, the establishment of performance requirements must be done within the local context of the project or built environmental standard under consideration. A performance standard without a local or judgement factor in North America is a myth, if the objective is executed construction rather than architectural speculation.

Performance requirements can only be established if the user's requirements are known. User's requirements mean not only what does the user want to do; how much space to do it in; what kind of sensory environment is needed; but also, what kind of quality, for what kind of cost, in what time frame, is necessary or expected.

The development of user requirements for a building is a mandatory step in the systems approach for any specific project. Without defined user requirements, it is not possible to prepare project-related performance specifications except in the most generalized manner. The three considerations of quality, cost and time set the immediate climate in which performance requirements must be established and met; together they articulate the local factor. Balanced consideration of these three criteria in defining performance requirements within the overall context of the user's requirements will ensure that the built industrial responses to a specification based on these performance requirements will have overall acceptability to the user.

Performance requirements must be established at two general levels to find practical application in a systems approach to building. First, at the building type level and, secondly, at the building part level.

The first level of performance requirements, that of building types, uses a generic view of all building whereby buildings can be placed in one of several generic categories. The generic categories of building amenable to performance classification and requirements definition on a national basis might be as follows:

1. Residential: Including low and high-density housing, housing for the old, student housing, hotels, nurses residences, hostels and all other types of building intended for residential purposes.

2. Lower Education: Creches, nursery schools, day-care centres and all primary and secondary schools.

3. Higher Education: Colleges, university buildings, research institutes.

4. Specialized Institutional: Specialized government buildings, corporate offices, industrial laboratories, other institutions.

5. Hospitals and Medical: All buildings used for the purposes of health care.

6. Office Buildings: All types of office building except those under the Specialized Institutional category.

7. Commercial: All types of retail and consumer service premises.

8. Service Industrial: Warehousing, and industrial premises incidental to urban service functions.

9. General Industrial: Manufacturing premises for light and medium industries.

It is also recognized that there are a number of building uses which, due to their specialized function or uniqueness are not amenable to generic classification. Within any society each of the generic building types listed has a given level of social importance and consequent level of quality. Due to the differing functions and levels of use for each building type, some difference of performance requirements will become apparent. This is not to suggest that materials or building methods suitable for one building type could not or should not be used on another; in fact a large amount of overlapping can be expected and should be sought for reasons of social economy.

Breaking building down generically and establishing an on-going process of user requirement analysis for each type, and from these analyses the performance requirements for each type, the technique of building in a given country can be made to respond with considerable sensitivity to the cultural values and economic priorities of that country. By this means, a climate is established in which performance requirements are expressed from a base which is culturally intensive rather than materially intensive, while at the same time ensuring the best use of a country's human skill and material resources. In systems jargon, the hardware fits into the software context, rather than the reverse. The trend in most countries which are using or are headed towards industrialized building at this time seems to be towards forcing societies into preconceived material or urban formats. A question of bending the people to fit the buildings rather than the reverse. I hold that the performance approach to building must express the full impact of cultural values together with those of function, cost, and time requirements to be specific about building performance. Implicit in this view is the notion that building, and particularly housing, should not be exported from one country to another in ready finished form, as has been the case with automobiles. Rather it is my view that each country or culturally distinct region* should establish its own performance criteria for the generic building categories and the building components within those categories.

Hopefully, there could be some international agreement on generic categories for building types, building sub-systems, and components. Through this matrix of internationally agreed upon generic categories for building types, sub-systems, and components, a systematic organization of performance requirements could be established. If it had a reasonable number of performance requirements categorizations, the matrix so developed could respond to a nearly infinite number of local user requirements. The combined effects of a generic base and user matrix would permit the movement of building parts between countries, while restraining the possibility of cultural swamping of the less developed and economically smaller countries by more highly developed and larger countries.

Such a matrix could form the essential quality control base of a systems approach to the organization of the world's shelter needs in a manner amenable to the prudent use of the world's productive capacities to the widest social betterment, while protecting the vital built expression of the world's mosaic of cultures.

The second level of the establishment of performance requirements concerns the requirement for the sub-systems and components of building.

The establishment of these performance requirements is characterized by what appears to be two divergent view points. One which divides a building into a number of pieces which may be called elements, units, parts, components, etc., and presents a performance specification for each primary material or assemblage of materials which may be used to make the element, unit, part, or component. The second view also breaks a building down into a number of pieces, usually known as sub-systems where each sub-system performs a function in a complete building (or building system) which is not duplicated in whole or in part by the function of any other sub-system. Under this mode of functional definition, solid walls, windows, doors, and grilles all form part of an exterior enclosure sub-system, while the heating, cooling, and ventilating provisions, together with all their controls and supplementary electrical services, would comprise the atmosphere sub-system.

The first approach to component performance definition breaks a building down into all the elements which are found in traditional trade-based construction, and provides a performance specification for each primary material used. In this method windows would be an identified component, and performance specifications provided for windows made of wood, steel, aluminum, and any other material in common use.

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*This view I have expanded in a paper entitled, "Building Standards for Systems Building," delivered to the International Systems Building Round Table Conference, Boston Architectural Center, November 17-19, 1971.

Similar specifications would exist for different kinds of solid walls, doors, and other items which constitute the exterior of a building. This approach constitutes the writing of performance specifications to replace prescriptive specifications in the traditional approach to building. To me, it appears to make the already complex traditional approach to building even more complex. It must be admitted that in some respects it offers the architect infinite choice, a choice which, I believe, few societies can afford, and one which in an overall sense appears to do little to raise the general standard of architecture. I believe this approach is not in fact a true performance approach as it starts with the prescription of the basic material to be used. It should perhaps be known as the Prescriptive Performance Specification method.

The second approach to component performance specification is that based on breakdown of a building into sub-systems. It is a common basis for taking full advantage of the systems approach to building. The sub-system breakdown which might be considered is developed for each generic building type identified. For housing the sub-system performance specification categories might be: 1) Structure/Ceiling, 2) Atmosphere, 3) Interior Space Division, 4) Exterior Enclosure, 5) Plumbing, 6) Electrical, 7) Roofing, 8) Stairs, 9) Bathroom, 10) Flooring, 11) Furnishing, 12) Finishes and Miscellaneous, 13) Non-system. For schools the sub-systems performance specification categories might be: 1) Structure, 2) Atmosphere, 3) Lighting/Ceiling, 4) Interior Space Division, 5) Exterior Enclosure, 6) Plumbing, 7) Electric-Electronic, 8) Caseworks & Screens, 9) Roofing, 10) Interior Finishes, 11) Non-system.

It is also common within the systems approach to define the required performance of sub-systems in performance terms only; where the performance specifications usually state the tests (if known) by which performance will be judged, and give a clear statement of sub-system interfacing responsibilities.

The careful description of mandatory interfacing responsibilities between sub-systems is the key element in ensuring high quality, cost, and time performance without resorting to the use of closed systems.

By using the mandatory interface approach, where a mandatory interface is deemed to exist where the parts of one sub-system touch, pass through, or influence the performance of another sub-system in a finished building; full advantage can be taken of the plant, and skill resources of the sub-system contractors, without extensive and rigid conventions on modular co-ordination, joints and jointing, and with only generalized dimensional co-ordination. The approach tends to reward innovativeness over conformity. It also tends to use the resources of a country's building industry more effectively by reducing the trend towards the development of many competing vertical trusts in building production in a given national market.

By describing only the required performance of a sub-system with no material references whatever, it is possible to consider on a direct competitive basis all available materials and methods offered. Assuming assessment of performance by a mixture of science-based testing and professional building (architectural and engineering) judgement, a balance can be struck between the subjective and objective factors which any building must fill. Where the building professional through his skill, integrity, and wisdom, enjoys the confidence of his colleagues, in building manufacturing and contracting; the primary use of his judgement to evaluate performance, supplemented by test procedures, ensures the rational use of the building industry's resources to the economic advantage of society in a climate of cultural betterment.

Taking a systems approach to the building industry itself, there appears to me to be a desperate need to increase user requirement knowledge and science-based skill in the building industry. This would best be achieved by very large increases in the budgets of National Building Research Agencies, making these agencies responsible for spearheading the development and dissemination of knowledge throughout national education systems, and the broadening of building professional research and development capabilities.

There appears also a desperate need to overhaul the structures of the building professions, trades, and regulatory occupations, to reduce the numbers of discrete roles and job classifications and to make user sensitive skills equal in importance to building science and technological skills.

Together, these two strategies, along with code and certification rationalization, will make the use of the performance concept in building a practical possibility and perhaps an accomplished reality.

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The Relationship Between the Performance Concept and the Systems Concept

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There is considerable confusion in current architectural, engineering and construction literature concerning the distinction and relationship between the performance and systems concepts. It would be useful to maintain a clear theoretical separation of these ideas. Although there is value in their simultaneous application to many types of project, each also has the capability for independent application to certain aspects of the building process. The rationale for this proposition is based on a comparative analysis of the two concepts in terms of definitions, objectives, origins, scope of applicability, and advantages and disadvantages.

Une confusion appréciable règne dans la littérature actuelle traitant d'architecture, de construction et de génie civil au sujet des rapports entre les concepts de performance et de système. Il serait utile de maintenir une claire différentiation théorique de ces idées. Bien que leur application simultanée à certains types de projects soit de valeur, chacune a la capacité d'être appliquée indépendemment à des aspects variés du processus de la construction. La raison d'être de cette proposition s'appuie sur une analyse comparative des deux concepts en termes de définitions, d'objectifs, de portée d'application, d'avantages et de désavantages.

Key words: Building industry; building production process; building systems; innovation; performance approach; semantics; systems approach.

During the last decade, discussions of how the building industry might be brought up to date seem invariably to refer, directly or indirectly, to two closely related ideas credited with much success in other, more efficient industries: the performance concept and the systems concept.

Unfortunately, the rush to transfer these and associated ideas, such as dimensional standardization and mass production, to an elaborately structured industry ill-prepared to receive them, has produced a great deal of semantic confusion along with the evidence of some genuine progress. The sources of this confusion lie in two broad areas of misunderstanding. The first is the set of unique characteristics which sharply distinguishes the building industry from most mass-production industries, raising serious questions of feasibility in the direct transfer of technology. The second, which is the subject of the present paper, is the nature of the performance and systems concepts themselves.

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[1] Architect

There has been a proliferation of definitions, descriptions and discussions of historical derivations of these concepts in the recent literature of architecture, engineering and construction. A great deal of this material, although well intentioned, is in fact inaccurate and often contradictory. For example, the impression is sometimes given that performance and systems, as far as building is concerned, are inseparable concepts, or even that they are synonymous. When Progressive Architecture devoted an entire issue (August 1967) to a discussion of the impact of systems analysis and operations research on the design professions, they dubbed these applications "performance design."[1][2]

Another popular misconception concerning the application of the systems concept to building is that its object is invariably to develop or use a building system in the sense of a kit of parts, or innovative hardware, although Ezra Ehrenkrantz states flatly that "Building systems may or may not be created by the systems approach [and] the result of a systems approach may or may not be a building system."[2] In his book on the systems approach, C. West Churchman defines a system as "a set of parts coordinated to accomplish a set of goals."[3] Since the distinguishing characteristics of a system are simply coordinated parts and common objectives, it is clear that the term is appropriately applied to software as well as hardware. Churchman himself discusses it primarily in reference to the former, as the underlying methodology in management science.

As similarly noted by John P. Eberhard, the term "system" "may be understood in two ways: as a noun or as a verb ... As a noun it describes a collection or set of objects and their dependent relationships ... As a verb we mean to describe a way of doing something."[4] Eberhard, of course, does not literally mean that the word "system" can be used grammatically as a verb. He is simply pointing out that when applied to construction, "system" may refer to an organization of physical elements, as in a structural system, or to an organization of activities, as in a prefabricating system. In other words, a system may be a process as well as a product; a "set of rules" as well as a "kit of parts." More typically, it is some combination of the two. Coincidentally, the term "building" has exactly the same ambiguity: it may refer either to the construction process, or to an artifact that results from that process.

There is, however, a critical distinction between the implications in the two forms of the two words. A building (artifact) necessarily involves building (activity), and vice versa. But a system-process (software) does not necessarily have a specific system-product (hardware), nor does such a product necessarily require such a process. Because both words in both forms are matters of common usage, this distinction is intuitively recognized by most people speaking ordinary English. Nevertheless, it is fairly subtle, and therefore easily missed when new and specialized terms such as "building system" and "systems building" are introduced, combining the two words without a common interpretation of the implied relation between the processes and products denoted.

The situation becomes even more complicated when the concept of performance is presented as a more or less integral aspect of systems building. The difficulty arises from the fact that the range of possible scales of reference is extremely broad. One can speak of the performance of the entire building industry in terms of production rates, environmental quality, provision of employment, etc., and one can speak of the performance of a nail in terms of withdrawal resistance, shear strength, corrosion resistance, etc. The systems concept, however, is usefully applied only to the larger scales of reference. Thus the entire building industry can and should be viewed as a system, whereas a nail, although certainly a component of many building systems, is not itself a system in any meaningful sense.

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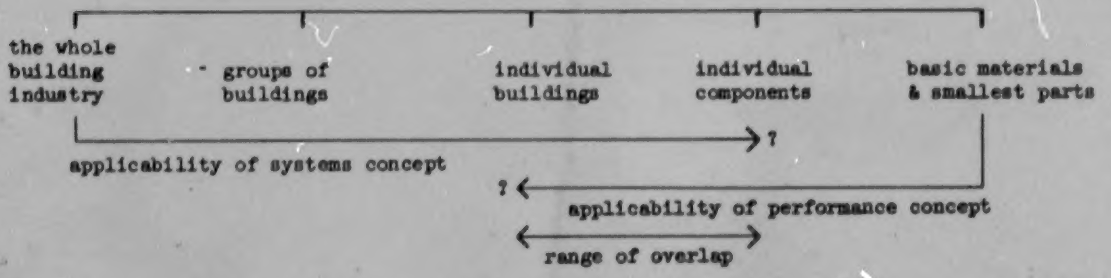
[2] Figures in brackets indicate the literature references at end of this paper.

A closer examination of the performance concept, on the other hand, indicates that for practical purposes, it is in fact applicable only to the smaller scales of reference. In their discussion of hierarchies of choice and performance in building design, Mainstone, Bianco and Harrison point out the basic difficulty of developing "pure" performance specifications, and then state, "This is particularly true at the higher levels such as that of the complete building, because higher level objectives and their associated requirements are, in general, less materialistic and less readily defined in unequivocal terms than lower-level ones." [5] (Incidentally, note the distinction between objectives and requirements.) They give further recognition to this difficulty when they state, "To simplify the discussion, the emphasis will be on satisfying individual primary requirements of the user -- for a comfortable air temperature or for a certain rate of air change for instance -- and not on any interdependence of or interference between these requirements. These are subjects calling for considerable further study."[6] They are also precisely the characteristic subjects of a systems analysis, which is at least as concerned with the relationships between requirements as with the requirements themselves. In fact, Bertalanffy defines systems as "sets of elements standing in interaction."[7]

In a paper on performance specifications, Harrison emphasizes that, "Before coming down to the specific requirements for a component ... decisions about the performance of the building will need to be taken, and assumptions made about how parts relate to the whole. Only then can the required properties and values be calculated for specific components."[8] In outlining procedural steps for the preparation of performance specifications, he starts by saying that, "The first task is to decide on the overall strategy for design of the building and its parts."[9] But in his commentary on current practice he uses two case histories to illustrate the problem of application and summarizes, "although there may be an attempt on the part of certain sponsors to specify at the higher levels, in practice they find this largely impossible without sacrificing their control of the performance of the final design, and indeed the overall acceptability of the final design. It is far easier, for example, to check a U-value than it is to work through a submitted design to calculate whether specified temperatures are likely to be maintained, especially when the products used, and their properties, may be unfamiliar."[10] At the end of the paper he concludes that "the use of performance specifications demands a more systematic approach to design than has been common hitherto."[11]

Thus it would seem that the systems concept is most applicable when the problem at hand is large-scale and more or less complex, includes values difficult or impossible to quantify, and calls for an emphasis on interactions. The performance concept, however, is more relevant to problems associated with individual components when the emphasis is more properly on measurable properties. It is also clear that there is a considerable area of overlap, in which problems are best addressed by some integrated form of the two approaches.

Range of Building Problems


the whole building industry
groups of buildings
individual buildings
individual components
basic materials & smallest parts
?
applicability of systems concept
?
applicability of performance concept
range of overlap

The reasons for this difference of scope lie in the differences between the problems the two concepts were developed to deal with.

The performance concept was developed by industry, and large customers of industry, to overcome inefficiencies caused by design preconception, to permit or encourage innovation, and to provide a better competitive situation between different products performing the same function. Its most typical mode of application is the performance requirement, a statement concerning the characteristics a certain product or set of products must have, without reference to how those characteristics are to be provided. Such a statement may take the form of a regulation or a specification. In either case, its intention is to provide designers and manufacturers with specific criteria while minimizing irrelevant constraints.

The systems concept, on the other hand, was developed first by scientists involved in basic research, and only later was applied to engineering, logistics, military operations, and management and industry in general.

A problem confronting scientists in many fields early in this century was that traditional analytical techniques relied on elaborate isolation of the smallest possible components of the subject under study, which in many cases failed to provide a suitable description of the behavior of the subject as a whole. This was particularly true when there were strong and complex interactions between the various components in their natural state of combination. These subjects, which had to be examined as organized wholes to allow further scientific progress, were given the general name of "systems."[12] These phenomena might be organized objects, as in the nervous system of an animal, or they might be organized events, as in an economic system.

In any case, the distinguishing characteristic of strong interactions between components gave a special meaning to the word "system" that has still not found its way into common usage. Thus the proper technological and managerial applications of the "systems approach" are, strictly speaking, only those situations requiring serious consideration of the effects of interaction. Systems analysis and systems engineering, and the related disciplines of operations research and management science, include techniques developed specifically to identify, measure, describe and control various kinds of interaction.

It can also be seen from this background that the two concepts in question are to be considered "new" in relation to more traditional approaches primarily in their shift of emphasis. The performance concept emphasizes ends rather than means, and the systems concept emphasizes the whole rather than the parts. Those who state that there is "nothing new" in these ideas simply fail to appreciate the actual and potential impact of such changes in basic attitude.

In the literature of systems and industrialized building, there is a tendency to identify these concepts with specific procedures or "methodologies." It is in such descriptions of procedure that one is most frequently given the impression that the performance concept is inseparable from the systems approach to building problems. When Ehrenkrantz outlines the general steps which characterize the systems approach, he includes the development of performance criteria and the evaluation and selection of alternatives in reference to them. However, he does not specifically equate these steps with the systems approach per se, and he points out that, "The order and degree of detail with which these steps are implemented depend on the nature of the problem." Furthermore, he lists as the first step in the total process the "statement of objectives."[13] It is clear that the term "objectives" applies to the system as a whole, whereas "performance criteria" applies to individual components.

Again, when Churchman lists the basic considerations of the management scientist studying a system, he starts with "the total system objectives and, more specifically, the performance measures of the whole system." A separate consideration is "the components of the system, their activities, goals and measures of performance."[14] But he is talking here about managerial systems, not hardware, and the components he refers to are groups of people oriented toward the same mission.[15] In any case, he does not mention a performance concept or a performance approach as such.

To take the systems approach to a particular problem in the building industry simply means to view the industry, or the group of buildings, or the building, or the functional category of components, or the production process, primarily as a whole, and to then proceed from generals to particulars with a minimum of preconceived notions. It also means the avoidance of traditional artificial exclusions of "outside" factors which may in fact decisively influence the nature of the problem.

But it is incorrect to say that because the systems approach necessarily involves the identification of objectives and measures of performance, it therefore incorporates the performance concept. The latter term appears applicable only to situations in which it is both desirable and feasible to precisely specify measurable characteristics of physical objects without reference to the particular means of producing them. Such situations are by no means invariably present in all building industry problems which could benefit from the systems approach. Conversely, the performance concept can be usefully applied to problems in which the systems approach has no particular relevancy.

An example of the first type of situation would be the development of a master plan for a group of buildings such as a university campus or a new town. The systems approach could be applied to the generation of the plan. Implementation of the plan could proceed by conventional design and construction procedures. Although *objectives* would certainly have to be clearly stated in terms which would allow reasonably unequivocal evaluation of the plan, there would not necessarily be any need for specifying the detailed *performance* of building subsystems or components, or for that matter, for the use of proprietary building systems in any form.

An example of the second type of situation would be the development of an innovative building product for the improved joining of specific components already in use. Performance criteria could be established for rigidity, water-tightness and other physical properties of the joint, allowing equal consideration of mechanical fasteners, welding, adhesives, etc. The systems concept, as distinct from traditional engineering procedures, would not be applicable in any practical sense.

Furthermore, both the performance and the systems concepts have certain inherent disadvantages which must be carefully weighed against their presumed problem-solving capabilities in any particular case. Implementation of the performance approach, for example, usually requires the development of precisely defined test procedures and a corresponding test program. It also may require special legal documentation which at present has relatively little precedent. Application of the systems approach may involve very elaborate analyses of the problem and evaluations of alternative solutions which cannot be justified in terms of time or cost-benefit. It is also susceptible to political sabotage because of the need for questioning existing procedures and other matters in which there may be sensitive vested interest.

Nevertheless, the two concepts do share a broad range of applicability to various types of building problems, particularly in the area of industrialization. Far from being mutually exclusive, they are usually complementary, and in practice are more often found in some combination than singly. In fact, there are cases in which a problem would be best solved by such a joint approach, but the attempt is made to handle the situation with techniques derived from only one source. This is perhaps most frequently true of direct applications of the performance concept to the development of building products without an adequate systems analysis of their context.

At least for the immediate future, therefore, it would seem best to proceed with the modernization of the building industry from a conceptual basis which maintains a clear distinction between the performance and systems approaches, recognizes the need to develop new systems in the sense of methods as well as products, and provides alternative combinations of these ideas to meet the wide range of specific problems with which we are confronted. Although neither the performance nor the systems concept offer panaceas, it would be unfortunate if their real value were dissipated through inappropriate and superficial applications.

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[8] Harrison, p. 1708

[9] Ibid.

[10] Ibid., p. 1709

[11] Ibid., p. 1713

[12] Bertalanffy, pp. 3-29

[13] Ehrenkrantz, p. 57

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Computer Based Code Systems and the Performance Concept

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Building codes are part of a building code system which is intended to provide an organized process by which such codes are: communicated, updated, enforced, administrated and evaluated. Historically this code system has been manually operated by the use of printed documents. There is some evidence to indicate that it would be economically and technically possible to convert most of this system to one which was computer based. A computer based code system could be self-improving, resource conserving, provide an information base to the design process, raise the level of sophistication of evaluation methods, and make the code requirements more nearly responsive to the performance requirements of building users.

Les réglements de construction font partie d'un système de réglements de construction qui doit fournir une méthode organisée suivant laquelle de tels réglements sont communiqués, mis à jour, renforcés, administrés et évalués. Historiquement, ce système de réglement a été traité manuellement au moyen de documents imprimés. On est gondé de croire qu'il serait économiquement et techniquement possible de convertir la plus grande partie de ce système en un autre faisant appel à l'ordinateur. Un système de réglements à base d'ordinateur pourrait être auto-améliorant, conservateur de ressources, fournirait une base d'information pour les études en cours, raffinerait les méthodes d'évaluation et pourrait rendre les exigences des réglements plus sensibles aux demandes de performance des usagers.

Key words: Building codes; building systems; computer systems; performance standards; simulation of building requirements; systems design.

Building codes are usually considered to be a collection of rules and regulations for how buildings are to be built that have been legislated in the interest of public health, safety and welfare. The codes are part of a building code system which is intended to provide an organized process by which such codes are: communicated, updated, enforced, administrated and evaluated. Building codes have a 4,000 year history starting in Mesopotamia and a 400 year history in the United States starting in New Amsterdam. The creation and enforcement of the code is the responsibility of the States as this power was not specifically delegated to the Federal Government in the Constitution.

However, this police power must be used within reason. The language and enforcement of the code cannot compromise any other rights guaranteed by the Constitution. The States have, historically, found it convenient to delegate their power of building code creation, adoption and enforcement to local municipalities. This has resulted in a proliferation of building codes with varying degrees of similarity and protection. The turn of the century saw the beginning of the development of model codes. These have developed in regional areas with the intent of insuring similarity of codes and adequate levels of protection of public health, safety and welfare. All codes claim to be based on the relationship of sound construction to personal safety with major concern for protection against health and fire hazards.

In recent history codes have been printed in documents and communicated to the designers or constructors of buildings by sending copies of such documents to them, or by having a building code inspector review working drawings and specifications and then telling the designer or constructor what has been omitted or done incorrectly. This process of communications and review is not only cumbersome, it is filled with problems. Some of the key problems are:

> --Building Code documents are all too often put on the shelf in an architect's or engineer's office and unused until there is trouble. The staff of the professional firm who are involved in actually producing the contract documents (working drawings and specifications) are not likely to be familiar with the detailed code requirements but depend on previous building solutions to provide a satisfactory model, or on the building inspector to catch any mistakes.
>
> --The building inspector cannot possibly review all of the details of proposed plans and specifications, so that there is a tendency to concentrate on a few areas of "normal" vulnerability and review only those limited aspects. Other possible code violations are left to be caught while the building is under construction, leading to costly corrections and prolonged legal battles.
>
> --The building inspector's office tends to be understaffed, and all too often not very productive, so that long delays are introduced into the building process by waiting for approvals. Where public health departments and/or federal agencies also must review plans for compliance with other requirements, the delays add up to months and even years.
>
> --There is little or no feedback built into the code making and review process. Hence mistakes made in the design of the code or the review procedures have little chance of improvement. Furthermore the ability to improve or amplify code requirements as new innovations are introduced into the building market is very limited. Most often innovations are handled as an exception granted to the code. This requires the innovator to apply for such exceptions in each jurisdiction in which he plans to market.

As though these problems were not enough, there is the further limitation of narrowly written code requirements. Building codes have historically been structured around the set of building products available at the turn of the century or shortly afterwards. These include the use of timber to frame houses (walls shall be 2 X 4's, 16" on center), plumbing, electrical, lighting, central heating, etc. The codes make almost no provision for entirely new concepts of providing for waste disposal or energy distribution or other types of innovations when and if they emerge. The building codes continually reference conventional materials like brick, concrete, stone and steel. They allow new materials like plastic only after long procedural delays and often only after unreasonable test requirements that are based on the characteristics of conventional materials. Existing building codes are also designed to be administered in the context of a building process which produces one building at a time under an ad hoc arrangement of designers and contractors. The recent emergence of industrialized building techniques has caused the development of state building codes specifically aimed at the regulation of buildings resulting from factory production. These new codes dealing primarily with manufactured housing are an open admission of the inadequacies of the existing code system.

There is a philosophical argument that can be raised about the existing code system that is also important to mention in this paper. Building codes have been developed within a philosophical system that places the object (a building or its parts) as central to its concerns. Principles are thus derived which express our concern with avoidance of defects in the object and with a language of regulation that is authoritative, purposefully allowing for little or no interpretation of underlying intent by the users of the code. A code is judged in practical terms by how clearly and unambiguously it states what must be done in constructing a building to avoid any defects which might prove hazardous to the safety or health of the public. A more recent recognition that the state police power may also be used to provide for the welfare of its citizens has caused some consternation in building code circles.

A philosophy of building which places the well-designed, safe and health-protecting building at its core has served us well as a guiding principle for more than one hundred years. Generations of architects, engineers, builders, and code officials have found a common value system to share even though they might argue about the best means of achieving good solutions or how to measure the results. Now this philosophy is being questioned by many of us, especially those young people in our universities who are being educated to assume future professional roles in the industry of building. Central to their philosophy --whether used to provide guiding principles for a government or a system of building-- is man. This shift in philosophy from the requirements of the building to the requirements of the inhabitants may appear minor to some, but it has major implications for the guiding principles of building from the role of architects to the formulation of codes.

During this past year a team of faculty members and graduate students at the State University of New York at Buffalo (SUNYAB) together with various consultants have been exploring the possibility of introducing a computer based system into the building code field with the express purpose of trying to improve the performance of the code system of the United States. Financial support for this program was provided by the National Science Foundation's RANN (Research Applied to National Needs) program. The goal has been to improve the code provisions and the code system of people, institutions and activities which surround the writing, communication, updating, enforcing, administration and evaluation of codes.

To accomplish this goal, the study team has approached the "building code field" at three levels:

> REQUIREMENTS, the individual provisions of a building code. Potential applications revolve around improved ways to measure performance via simulation, and because of the power of the computer, new areas of performance which might be desirable to measure.
>
> USER PATTERNS, the ways and means by which the various users of a building code identify and execute the numerous code provisions. Potential computer applications to assist a code user to apply or utilize a code include better ways to communicate requirements (information systems), sequenced ways of presentation (design tools), methods to determine code compliance (evaluation systems), and aide in administering necessary tasks (management systems).
>
> INSTITUTIONS, the many organized groups involved in the building code field, including Federal Agencies, Model Code groups, testing laboratories, municipal building departments and many more. Applications include ways of storing and disseminating information (record keeping and information systems), data collection and analysis systems (statistical applications).

Computer applications have been developed at each of these levels; more are in the planning stages. Potentials for innovative applications exist at all three levels and the study team intends to explore each of these.[1]

The team has developed the performance criteria which it believes a building code system might aspire to if it were computer based. These include the intention that the system:

--be self-improving in nature. That is, that the design of the system contain provisions for continuous updating at a minimum of effort.

--require either substantially fewer resources than the present systems to operate and/or make much more effective use of the resources available to the system.

--present information as it is needed in the design/development process in order that all concerned can make appropriate decisions. This includes the spectrum of users from public officials, to designers, owners, occupants, builders, manufacturers, etc.

--should provide guidance to the users of the system rather than be limited to identifying violations. It might actively assist its users in other functional tasks for which the data required to make a code review could also be applied. It should promote an understanding of the reasons for and the nature of the various requirements to help avoid unjust criticism of being arbitrary or irrational.

--help to pinpoint responsibility for decisions and compliance so that failures are consistently identified with such responsibilities.

--be supported and maintained by competent professionals whose skills are fully utilized in those areas requiring judgment rather than in thousands of minor routine tasks.

The SUNYAB research program has been organized to attempt to accomplish these goals and help the code system of the United States to move towards meeting these performance criteria. The project does not begin from scratch, because there is not only a body of computer programs which have been developed in the building field, but there have been a few projects specifically aimed at exploring computer potential in the code area.

In 1965, the National Bureau of Standards began a study entitled, "A Study of the Feasibility of Development of Computer-based Systems for Semi-Automated Comparisons of Building Designs and Regulatory Code Criteria: A Computer-based Code Checking System." This project was organized by the author and managed by Gary Stonebraker, then on the NBS staff.

Under the load of processing 500 project applications and approximately 1400 design submissions per year, the professional staff of the Architectural and Engineering Branch, Division of Hospital and Medical Facilities, U.S. Public Health Service, found it increasingly difficult to spend time in the field in the critical capacity of consulting. In order to relieve the professional staff for fuller participation in positive guidance in the development of a facility and in order to assure that program growth would continue without diminished effectiveness, a solution was sought by which to relieve the professional staff from the routine chores which are normally associated with code checking and enforcement.

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[1] This paper was prepared in the Fall of 1971. By the time it is presented in May of 1972 a number of actual demonstrations of the principles involved in utilizing computer based systems in the building code field will have been developed. Perhaps there will be an opportunity at the symposium to show some of these demonstrations.

The findings of the NBS study were as follows:

1. It was technologically feasible to develop a computer based system for the comparison of building designs with criteria set forth by regulatory codes. Two alternative systems for data processing were identified by which the man-machine interaction would positively effect the review procedure.

2. The development of a computer-based system for the comparison of building designs with criteria set forth by regulatory codes was economically feasible. This economic feasibility was based on several considerations, not the least of which, was that a computer-based system would be able to replace approximately 50% of the man-hours spent on the review process; therefore, the major benefit would be the relief of skilled man-power which at that time was valued at $175,000 per year. Other benefits were determined to be:

   A. The provision of detailed data files on each design submitted at each phase of submission, in form suitable for statistical analysis by computer. This would allow analysis of space usage, regional and building type of costs, etc. on a detailed current basis, and other options.

   B. Assurance that all criteria in the computer system were applied to every project, and applied uniformly and objectively.

   C. Ability to expand program capability more readily through decreased dependence upon scarce skills.

   D. The ability to use existing professional skills in more critical roles.

3. Such a system could be developed and applied specifically to the problems of comparing hospital designs with requirements set forth by Public Health Service regulations.

4. A system could be designed to accept a description of a building design and to automatically compare that data to any precisely defined criteria. A full review of the comparison could then be given back to the professional architect employed by the code system, who would examine any exceptions found, and only those exceptions.

5. By using such a system the professional would be relieved of much of the duty of routine checking of documents. The extent of the relief is estimated at 50% of the amount of work that is now done. The remaining 50% of the work involves operations calling for general professional judgments and interpretations, and this remains the resonsibility of the code professional.

In general the development of a computer-based code review system was determined to be both economically and technologically feasible. Such a system would allow review professionals to concentrate on non-routine matters. The computer would improve the services of the system by allowing the addition of capability not possible on a manual basis. Also the system could provide detailed files and descriptions of all buildings processed, which could prove useful in program analysis.

It was on the basis of the NBS study that the new SUNYAB project began by accepting the assumption that computer based systems for code review and evaluation were, under certain conditions, technically and economically feasible. The SUNYAB project wished to go beyond these findings.

We know that there are also a number of previous programs that have been written to simulate building conditions in order to evaluate them. One of the simplest simulation applications was reported in the August 1967 Journal of Fire Technology, a publication of the National Fire Protection Association. The problem was sprinkler design, specifically an insurance company's need to determine if submitted sprinkler plans and specifications were well enough designed to qualify for the low rates for sprinklered buildings. The conclusions of the authors was that almost any system can be economically reviewed via computer simulation at a service cost including the cost of engineering time, keypunch time and computer time at a fraction of that cost required for hand calculations of this type.

In November 1969 issue of this Journal, there was a report on a project by Richard Barrett and David Locklin of the Battelle Memorial Institute simulating smoke movement in high rise buildings. The approach was the development of an analytical model by which the spread of smoke throughout a tall building could be traced under a variety of fire and physical conditions. While noting the need for better information about the performance of various types of construction assemblies as actually constructed, these authors conclude that the developed method, "is useful in identifying the nature and location of smoke movement hazards created by stack effect in a particular building. Further, the magnitude of these problems can be predicted, and the effectiveness of corrective means can be assessed prior to building construction."

When some of these earlier computer demonstrations are linked to the concept of performance based code requirements a number of possibilities present themselves for exploration. When forecasts are made that indicate that in a few more years computer hardware will be many times faster, much smaller in size, and considerably less expensive it seems important to examine ways in which the capabilities of the computer might be used to improve the code system. When improved systems capability is possible, and when this improved system also makes possible a more dramatic shift to performance requirements, state governments will want to know how they can take advantage of this potential in the public interest.

It will likely be demonstrated by the SUNYAB project that it is technically feasible and economically possible to centralize at the State level the maintenance and operation of a computer based building code system. District offices in various locations throughout a State could be linked to the main computer facility through remote terminals that would serve to transmit information about building plans and specifications for review by the computer system. Any exceptions to stored code requirements would be printed automatically and become the concern of the professional staff of the Code Commission. This will, of course, relieve the staff of routine review tasks and make greater use of their professional skills. It would also be possible for professional firms to have their own remote terminals linked to the State Commission's computer system and to be able therefore to get code reviews made directly. By further development the State Code Commission could provide as a by-product of their review additional services like preliminary design reviews that suggest improvements before working drawings are made; the preparation of charts like door schedules or hardware schedules; educational interactive programs on the remote terminals for new employees in professional firms, etc. The plan reviews made by such a system would be more thorough than present manual methods, and thus help the State carry out their responsibilities in a more complete manner. The SUNYAB project should be able to demonstrate the feasibility of such a working system by putting together actual remote terminal equipment linked to our University computer. By the Fall of 1972 a report on the SUNYAB project should be available to any one who is interested in this aspect of performance based code systems.

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Performance Analysis

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A performance analysis technique for building elements, products and materials is described. In order to be able to evaluate the total performance of an object all influencing factors must be known. The technique is based upon the listing of the external factors affecting the object. The internal factors of the object have to withstand the effects of the external factors. By juxtaposition of the external and internal factors, requirements concerning the desired properties can be written. The analysis can be made by the aid of check lists for external and internal factors.

Une technique d'analyse de la performance pour les éléments de construction, les produits et les matériaux est décrite. Pour être capable d'évaluer la performance totale d'un objet, tous les facteurs qui exercent une influence doivent être connus. La technique est fondée sur l'énumération des facteurs externes affectant l'objet. Les "facteurs internes" de l'objet doivent résister aux effets de ces facteurs externes. En juxtaposant les facteurs externes et les facteurs internes, les exigences concernant les diverses propriétés peuvent être rédigées. L'analyse peut être faite avec l'aide de différents types de listes de contrôle pour les facteurs externes et internes.

Key words: Application of performance concept; building levels; external factors; internal factors; performance analysis; performance evaluation; stages of building.

1. Introduction

The application of the performance concept to buildings is considered as a total treatment of the problem where the influence of all aspects has to be accounted for. The performance concept implies that solutions are wanted which give optimal service under the influence of all factors affecting them in use.

In order to ensure completeness of the treatment, not only user's requirements but also the goals of the building technology and the society have to be considered. The performance concept may be applied at different levels of building and in different stages of the building process.

In the paper an analysing technique is described where the derivation of the external factors affecting the performance is taken as the starting point. After this, the internal factors - properties - of the object are listed which are needed to ensure the optimal performance. The matching of the external and internal factors forms the central point of the method.

The results may be presented as different types of performance statements, or performance requirements. The application of the concept to development is especially important.

Examples on the application of the system outlined above are given in five papers offered to this Symposium [1] to [5].[1]

2. Levels of application

The performance concept can be applied at different levels of building (Table 1), and an analysis performed at any level forms a part of a system.

Table 1. Examples of levels of building.

Regional building
Urban building Rural building
Group of buildings
Building
Space
Part of building
Building element combination
Building element
Part of building element
Product combination
Product
Material
Internal structure

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[1] Figures in brackets indicate the literature references at end of this paper.

The resulting "performance statements" are written in a different language from level to level. The statements on a certain level have to be translated and transformed in order to arrive at technically feasible solutions. The interconnection between the levels is poorly developed today.

It is evident that the complex can often be treated from a more technical point of view at the lower levels. However, even in cases where the efforts are concentrated, for instance, at the level of "product" it is always necessary to keep in mind the changing demands of the user, the technological resources and the ascertainment of the general welfare.

The terminology especially on the lower levels is confused and in Table 1 the general principles of the CIB-paper [6] have been accepted. A "component" does not form a part of the hierarchy, nor has it been defined, but according to the levels of Table 1 a component may belong anywhere from the level "product" to "part of building".

3. Stages of application

The performance-concept applications deal mainly with the end-use conditions of a building or another object.

Performance statements may, however, be set up at different stages during the life time of a construction. Some stages are listed in Table 2. All stages need a careful appraisal according to the general principles. A satisfactory "operation" demands the fulfilment of certain requirements concerning, for instance, "storage" and "transport".

Table 2. Stages of application of the performance concept.

- Before end-use conditions
    - Manufacture
    - Storage
    - Transport
    - Construction, including newly erected or installed construction

- Use conditions
    - Operation
    - Maintenance
    - Repair
    - Replacement

- Demolition

4. Parties concerned

However important the user needs may be considered, neither they nor the technology alone can be accepted as sufficient in circumstances where the demands of the "society" as a whole have been neglected. This point of view is especially important in the technological society of today. On the other hand, it is very important to have the technology very tightly bound to the procedure from the start in order to ascertain that the technological objectives will be directed in the proper manner.

Therefore, the possible needs, values and goals of the user, of the society as a whole or of its subgroups, and of the building technology, have to be clarified. The needs, values and goals are truly problematic and they might be roughly divided into three groups:

-unchanging,
-slowly changing, and
-rapidly changing.

The performance concept cannot solve problems in itself, but the correct use of its principles could make unnecessary some of the friction in the society as it would put forward a common philosophy for the triangle, user - community - building technology, and aid in the establishment of a more normative approach in building.

5. External and internal factors

5.1. General

In many cases the performance concept is treated as if it is very easy to derive different kinds of performance requirements from user needs. However, this procedure is very complicated.

The analysis technique presented in this work is based upon the juxtaposition of external and internal factors. This kind of technique works as follows: all the external factors which affect the object are listed and the external factors are then compared with the corresponding properties of the object. It must be borne in mind that the most serious effects are often the result of a combined action of a number of external factors.

The internal factors consist of properties of the object. To permit the definition of these properties, processes which may take place under the action of the external factors have also to be accounted for.

The performance analysis technique is intended for levels up to that of building elements. It is likely that the technique is also suitable for higher levels of building, at least to some extent. The conceptions on these levels have to be defined and analysed according to the systematics.

The technique tries to achieve a procedure of systematic analysis and evaluation of building products based upon their total performance as parts of the building. This provides an opportunity to take all essential factors into consideration. The procedure also explains the reasons for the setting up of a certain set of requirements and consequently, answers the questions on which requirements are set up, and why this has been done.

5.2. External factors

Table 3. List of external factors which affect an object in use.

1. Human goals
    - Physiological, anthropometrical, psychological, sociological
    - Transformed into technical terms
2. Environmental factors and agents
    - Loads and forces
    - Water and moisture
    - Heat
    - Fire
    - Air
    - Electricity
    - Sound
    - Radiation
    - Materials and products
    - People
    - Animals, plants and micro-organisms
    - Machines and means of transportation
    - Installations and equipment
    - Time
3. Economic factors
4. Legislative factors

The external factors affecting and deciding the performance are listed in Table 3. At first, the human goals, also called human requirements, are given in two forms. It is sometimes possible to translate these factors into technical terms; it is also possible to use a different terminology on different levels of building, e.g., it may be possible to define the project only in non-technical human terms. The second category of external factors consists of environmental factors and/or agents which impose requirements on the properties of the solution. The factors concerned with economy are often decisive. Legislation, building codes, norms and standards often indicate the limits within which the solutions must fall.

5.3. Internal factors

Table 4 gives a picture of the present form (September 1971) of the list of internal factors [7]. The list will, of course, become different if other levels are considered.

Table 4. List of internal factors.

Material and product level:
- Mechanical properties and processes
- Elastic and rheological properties and processes
- Hydrophysical properties and processes
- Electrochemical properties and processes
- Thermal and thermodynamic properties and processes
- Electrical and magnetic properties and phenomena
- Acoustic properties and phenomena
- Optical properties and phenomena
- Radiation
- Chemical properties and reactions
- Biochemical processes
- Structural properties and processes
- Physiological and hygienic properties
- Form and appearance
- Economic factors

Level of internal structure:
- Elastic and rheological properties and processes
- Thermal and thermo-dynamic properties and processes
- Electrochemical properties and processes
- Electrical and magnetic properties and phenomena
- Acoustic properties and phenomena
- Optical phenomena
- Structural properties and processes
- Chemical properties and reactions

6. Performance evaluation

The philosophy of performance evaluation has to be developed further. The old way of looking at standardized methods which give reproducible results but without any real connection with the behaviour of the object in practice, has to be rejected. In this connection, it has to be emphasized that Weil recommended at the meeting of the Permanent Committee of RILEM in Lund 1970 a critical reappraisal of all existing testing methods [8].

When different requirements are looked upon, there seem to be some which can be looked upon as objective, and others which are very subjective. The former may often be expressed in completely technical terms, the subjective variety may in some cases be measured but the evaluation may be more psychological than anything else.

Table 5 shows some of the levels from Table 1 and indicates some possibilities of evaluation. It is not always necessary to base the evaluation on tests, measurements, judgments, etc. made at the same level which is evaluated. The level considered in Table 5 is a building element. The element itself may be investigated in some cases but in others there are possibilities to evaluate the performance of the building element from a lower or higher level. These opportunities have to be very carefully appraised when the applicability of the materials science approach to performance evaluation is considered.

Table 5. Examples of different ways to make performance evaluation of a building element.

Level	Evaluation performed at the level						
Space	x						
Building element	↓	x	↑	↑	↑	↑	↑
Product			x	x		x	
Material				x	x	x	
Internal structure						x	x

For instance, in [2] an example is given where a masonry mortar ("product") is evaluated by studying the interaction between the mortar and masonry units ("product combination"). Some properties of a masonry wall ("building element") may be evaluated in this way, too. The possibilities to base the evaluation of performance characteristics on basic parameters is looked upon in [5] where pore properties in performance evaluation are considered.

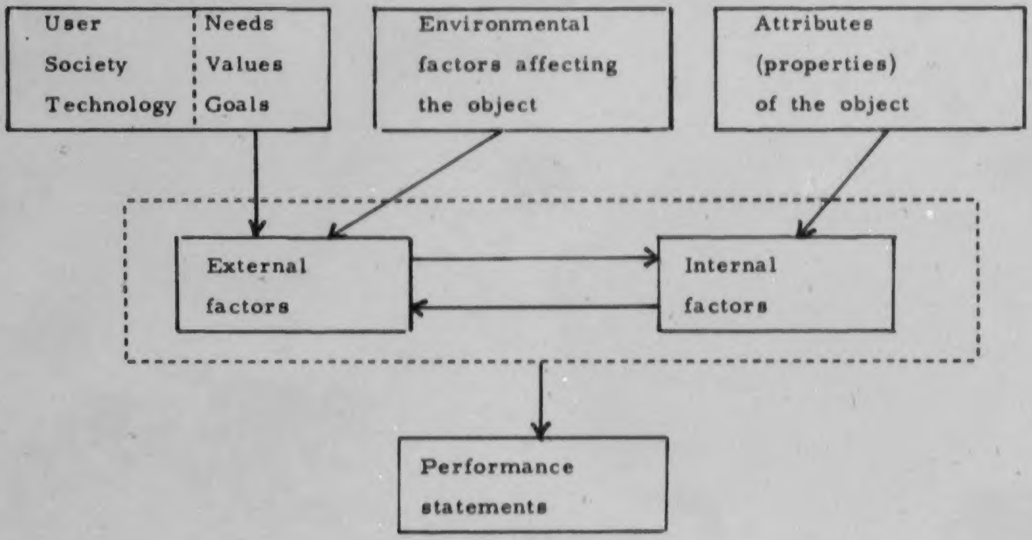
It is possible to obtain relevant information concerning the relationship between the expected and the achieved performance by analysing practical experience, but it has to be kept in mind that this is not always possible. If the pace of development is very fast, the feedback mechanism may work too slowly, and one of the main objectives of the performance thinking is to take all possible measures to avoid bad results. In extreme cases, the situation cannot be remedied afterwards at all.

8. Conclusions

The paper deals with a performance analysis technique which is based upon the interaction between external and internal factors. Table 6 illustrates the general principles. The external factors are derived from the goals of the user, building technology and society from the one hand, and from the environmental factors together with economic and legislative factors from the other. The internal factors (attributes, properties) have to be chosen in such a way that the solution gives us service under the influence of the deciding external factors.

Table 6 does not deal with any methods or techniques which would be needed to collect, use and transform knowledge in order to arrive to a set of data which could be used for decision making. This mechanism is rather poorly developed today.

Table 6. Performance analysis based upon the interaction of external and internal factors.


User
Society
Technology
Needs
Values
Goals
Environmental factors affecting the object
Attributes (properties) of the object
External factors
Internal factors
Performance statements

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Building Performance Appraisal

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This paper outlines a model of an interactive system with five main components:

(1) the goals and objectives of an organisation;

(2) the activity and behaviour appropriate to the achievement of these objectives;

(3) the environment suitable for the activity;

(4) the hardware required for the creation of a suitable environment; and

(5) the resources required as inputs into the system and the values achieved as outputs.

It sets out the main stages in appraisal — modelling, measurement and evaluation, and then discusses the role of performance criteria under three categories: the "ideal", norms and constraints. The paper concludes with a brief reference to a published appraisal of a school and some of the findings resulting from it.

Cette communication présente dans ses grandes lignes un modèle de système d'action réciproque avec 5 composants principaux:

(1) buts et objectifs d'une organisation;

(2) activité et conduite propres à atteindre ces objectifs;

(3) le milieu convenable à cette activité;

(4) matériels requis pour la création d'un milieu convenable; et

(5) les ressources requises comme apports au système et les valeurs obtenues qui en résultent.

La communication indique les phases principales de l'étude - établissement du modèle, mesurage et évaluation, et examine ensuite le rôle des critères de performance classés en 3 catégories: "l'idéal", les normes et les limitations.

La communication conclut par une brève référence à l'étude publiée d'une école et aux informations qui en découlent.

Key words: Appraisal, building performance, constraints, environmental system, evaluation, resources.

1. A Systems Approach

A building, as any part of the environment, is a system. Since it is designed and used by people, and continuously adapted by people, it has at least two main parts — an animate one and an inanimate one. The Building Performance Research Unit in the University of Strathclyde in fact divided the system into five main parts related to each other in a manner which figure 1 attempts to illustrate (1)[2]. Although the figure shows the developed curved surface of a cylinder, with the implication that it is a closed system, this is clearly merely a convention. For in reality any system like this is open to similar systems around it, and to other systems which form its context; for instance the social, political and economic environment; the site; the climate; the traffic routes and access points. The five parts are, briefly:

1.1. The Objectives System

Any group or organisation has general objectives and immediate goals. The achievement of these is the basic driving force behind the behaviour and activity of organisations, or individuals for that matter. There may be conflicting goals; and there are always conflicts between the goals of the organisation and those of individuals or groups within it. The resolution or containment of these is an important objective in itself. The objectives indicated, such as productivity, adaptation, survival and morale are quite general ones drawn from the study of organisations.

1.2. The Activity System

This contains the categories of empirically observable activity patterns. Obviously all organisations have workflow, or productive activities. They all have special communications; they distinguish themselves from the surrounding environment, and distinguish between their parts, by identity-creating activities, and they all encourage or tolerate a host of informal activities (one way of containing conflicts of goals and objectives). An all-important class of activities is that which controls all other activities — control. This involves receiving feedback information on all activities and sending out instructions to alter them. One important piece of information received will be about the state of the physical environment (see system 3 below) in which the activities take place. If there is a misfit, not only will the activities be changed, but an instruction may be issued to engage in a special kind of productive activity — making or changing a piece of environmental hardware, to change the environment. Thus a part of control is concerned with making what are traditionally called 'design' decisions. These are often made on behalf of organisations by professional designers; their decisions are often carried out by specially hired productive units — contractors. So within the system there is a small sub-system which is truly generative and largely shapes the development of the whole system. The full political and social implications of this cannot be worked out here (2) but it must be noted that the question of who designs, for whom, has to be answered in order that performance criteria can be meaningfully discussed.

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[2] Figures in brackets indicate the literature reference at end of this paper.

1.3. The Environmental System

This has two main sub-systems; the physical environment and the spatial environment. The former has those characteristics which can be sensed by the normal perceptual processes; belonging to experiences of hearing, seeing, thermal sensation, smelling and touch. The latter is described in terms of spatial shapes and volumes; relationships between spaces and topological and geometric concepts.

1.4. The Building System

This, with its three sub-systems of fabric, services, and contents, is the hardware which generates the man-made environment. All its parts are those tangible pieces which are normally represented in drawings and listed in bills of quantities.

1.5. The Resources System

Three of the four systems described above consume resources; these resources can be regarded as system inputs. The fourth, the objectives system, produces values (in so far as any objectives are met) and these can be regarded as system outputs. The building costs something to provide. The environmental system costs something to maintain, in energy, cleaning, maintenance and repair. The activity system uses resources for salaries and wages, advertising, materials, and a host of related items. The objectives, in the degree to which they are met, have values. In theory, if all inputs and outputs can be made commensurate, say in money, then the model can be used for cost benefit analysis or investment analysis.

It has been pointed out that design is part of the normal control activities in any organisation. Its objective is specifically to provide the best environment for the organisation's needs, and in fact to bring the whole system into the best balance at any one time. At the interface between the environment and activity systems there goes on a complex series of interactions in which people exert various pressures on, and cause changes in, the environment, and in which the environment in turn limits, encourages, and in other ways influences their behaviour. At this interface a kind of dynamic homeostasis is reached which utilises the adaptability of both people and things to their maximum. It is at this interface, too, that the psychological reactions to environment would occur and (perhaps) be measurable. Such notions as privacy, meaning of the environment, likes and dislikes would all be explored here.

Many models of design, or design-decision-making as it is now fashionable to call it, exist. Some are linear, others iterative, others full of complex feedback loops. There is however no agreement on the validity of these models; or even where the elements are agreed, there is disagreement as to the time sequence in which they occur. There is one level of model however which is useful, though general, and which has met with a wide consensus of agreement. It is that which includes in any single complete decision sequence a stage which is concerned with understanding the nature of the problem, structuring it, and gathering and sifting seemingly relevant information; in short, analysis. It then specifies a further stage concerned with putting forward part or whole solutions; acts of creative generation of patterns, relationships, structures; synthesis. Then it specifies an introspective act, where the designer looks back at what he has done and somehow appraises its quality. In the light of this appraisal he makes a decision to finish, proceed, or return to start the design again or amend it; or perhaps to seek a new and more thorough understanding of the problem. It is not significant if he starts with synthesis as a way of exploring the problem, or with analysis; the appraisal always takes place. And it is this act of appraisal that is crucial to developing a proper performance concept of building or other designed systems.

2. Appraisal

It is convenient to break this activity down further into a sequence of three parts. The first essential in any appraisal is to have an appraisable object; that is, to represent the concept in some tangible or specific form. There are many methods of representation possible; physical analogues (e.g., drawings, three dimensional models); electrical, water or mechanical analogues; mathematical models (equation sets); mathematical simulations; verbal descriptions; and a host of hybrids. The choice of appropriate model will generally be governed by the following factors:

(a) The type of problems and type of solution. A representation suitable for a machine may be unsuitable for a building.

(b) The stage in the design. A different model is likely to be needed in the early, general stages from that at later, detailed stages.

(c) Cost

(d) Reliability

(e) The type of measurements to be made later on the model. No model fully and adequately represents the real system. It is essential however that it should not distort those features which are to be measured. For instance the appearance of a drawing may positively mislead an observer looking for aesthetic characteristics. An economic model will not describe the environmental qualities of the object; a static one will not show the consequences of dynamic processes.

A general theory of validity has to be applied to all models. Although to scientists, physical (experimental) and mathematical models must undergo the most rigorous tests for validity, in building we have neither the theory nor the tests to be reasonably sure that any of our models work.

Having selected and made a suitable model, the designer can now measure its performance. Measurement implies the use of scales and quantities and this implies that both actual and desired performance must in some respects at least be quantifiable. Measures of building performance may relate to the provision of space; the circulation distances between activity-related spaces; thermal, visual or aural characteristics; building or running costs; site utilisation; adaptability; the level of service availability; or the rate of obsolescence.

Many measurements can be automatically performed by computers on a suitable input — alpha-numeric or graphical. The Package for Architectural Computer Evaluation (PACE) developed at Strathclyde (3) is one system for computer appraisal.

After the battery of measures have been completed, the natural question arises "what do the results mean?". This is where the third, and most difficult operation in appraisal starts — evaluation. Here the decision-maker is back in a value-laden, moral or ethical situation, where value systems, priorities, weightings, political position and deeply felt personal preferences will all affect his decisions. During the measurement stage the process is basically neutral; it simply produces results, whether good bad or indifferent is irrelevant. For evaluation to be successful, all these disparate results now have to be compared to criteria. Often these will not have been explicit in the problem structure. The results will have to be examined to see if they break any legal, cost, or self-imposed formal constraints. They will have to be seen as a set of results, and considered against such properties which were difficult to model, or perhaps modellable but unmeasurable. Moreover the weak points of the solution must be pinpointed so that remedial design action can be taken. The basic process however is a comparative one; the set of results as a whole, or each individually, is compared with some performance characteristics — criteria — which are expected, or must be met. How are these criteria derived?

3. Performance Criteria

Observation indicates that three types of criteria are commonly used.

3.1. The 'Ideal' Solution

This might be a building with zero circulation distance, or no running costs, or with a set of spaces each of which is suitable without the expenditure of any effort or money, for any of the original or future activities to take place. Although such ideals are rarely stated, they are often implicit in the measurement of such things as circulation distances, running costs, or space usability. The distance of any solution from the ideal — a true zero — is a useful indicator.

3.2. Norms

Many designs are judged on how good they appear to be within the currently acknowledged standards for that class of object. This is a particularly meaningful evaluation for those with a lot of relevant experience. So if there is data on the range, and, say, mean values, currently achieved in the solution of similar problems, one can place the specific performance on this range and see whether it is below, near or above average. This is an important evaluative technique. It involves continuous gathering of data on the performance of similar objects, and storing this data so that it can be continuously referred to. The data might include not only existing buildings of a similar function and type, but also performance of designs, including previous solutions by the designer in the specific current exercise. Computers are of course ideally suited for gathering, storing and retrieving such data.

3.3. Constraints

Early on in the analytic stages the designer will have discovered a host of legal, semi-legal (Code), cost, and other constraints. His evaluation must check whether the performance of any part on any count breaks any constraint. He may well discover that several are mutually exclusive and that some have to be broken for a solution to be feasible; another way of stating this is that the feasibility study which is characteristic of many early design processes is really an examination of the shape of the solution set.

4. Performance Evaluation

Making performance explicit on a rich variety of counts does not necessarily make evaluation of the whole system easier. It may do the opposite. Where in the absence of performance data the experienced designer is often able to make reasonably good guesses when faced by a rich but obviously incomplete set of data, he may feel unable at first to exercise his judicial skills. But with use, he develops a new ability; that is to recognise the interactions between elements of the design and to see how sensitive performance on one criterion is to changes in performance on other criteria. For instance he will discover how environmental standards vary with cost, or services provision with circulation routes and distances.

The process of comparing measured performance with criteria implies that performance criteria have been expressed in a language which is similar in form to the performance results. The model of the system described in Section 1 shows that performance can be described in at least five ways. First, a component or sub-system can be described in hardware terms; a drawing, with notes on dimensions, weights, physical properties etc. Second, it may be described in environmental terms; and for some curious reason a specification which defines, say, the limiting sound absorption or light emission of a component is often referred to these days as a 'performance specification'. This is merely one of many types of performance, as the rest of this paper shows. Third, it may be described in terms of people's responses to the system; their likes, complaints, work-performance, visual error, or cognitive understanding of the system. Fourth, it could be described in terms of its ability to attain objectives such as production, morale, or survival. Fifth, it can be described in resources terms; capital or running cost. Any of these descriptions, properly defined and codified can become a perfectly proper performance statement. If it is prescriptive, it is a criterion; if it is descriptive, it is a measurement (real or estimated). The all-important thing is unity of concept and language. It is no use specifying a piece of hardware unless its human consequences have been tried and tested and are known. In an uncertain situation it may be better to specify the human response and leave it to responsible research and development organisations to make the link to hardware.

A unifying measure of performance, usually cost, is a powerful way of avoiding the difficulty of judging on several criteria.

One interesting question in using performance criteria concerns the mechanism of change. This paper can only suggest the mechanism. It appears that the economic state of an individual, organisation or state has crucial effects on the standards accepted and expected. Technology is another powerful standard changer; especially where an improvement makes possible a higher standard on no extra cost, or less-than-proportionate cost. Cultural factors loom large too; for instance, standards of sound insulation derived from work on working class British, wartime populations, are totally meaningless in village cultures of, say, the Far East.

5. The 'Real' World

A building, used and fully occupied, is in no sense more 'real' than a good model of it, used perhaps during its design. It is just a different kind of model; more detailed, more complete, but also in some respects less amenable to measurement. The 'real' thing is the concept in the head of the designer; any concrete model of it is bound to be less than complete. Once buildings in everyday use are accepted as just different kinds of models, measurable and instrumentable, then the feedback obtained after the event, so to speak, will seem to be just as relevant as that obtained on more classical models during design. Both sets of data will flow together to enrich the consciousness of designers; to enable them to set performance standards and to appraise their own and others' solutions more critically.

One aspect of the 'real' world which appears not to be amenable to modelling is the dynamic behaviour of the system described in 1. above. Initially there is an organisation, with objectives and planned activities. The hardware and environment exist only conceptually or on paper. Immediately the building is built and occupied it enters the phase of continuous re-design, change, obsolescency, and adaptation. Figure 2 attempts to show the system in a third, time, dimension, as a solid block. At any point in time a snapshot of its state can be obtained by slicing the solid. One slice changes into the next as a result of formal control (design) and produce (construct) decisions and also as a result of day to day informal design and construct decisions by the users of the system. This process is poorly understood. Yet an understanding of it would show what performance really means — those characteristics which make an impact on behaviour.

6. Examples

BPRU has carried out appraisals on both models and real buildings. Perhaps the best example is that carried out on a secondary comprehensive school in Ayrshire (4). Here measurements were made of:

(1) Space utilisation, and the match between curricular desiderata and space

(2) Capital and running costs

(3) Activity costs

(4) Two and three dimensional compactness

(5) Circulation distances

(6) Day and electric lighting levels

(7) Energy consumption for heating

(8) Teachers' responses to various aspects of the school and their own classrooms

(9) Informal social behaviour and location of gathering places

(10) Circulation rules for controlling flow of traffic.

The results show that even in a building type which is typical and in many ways 'average' there are factors which would remain unnoticed without systematic performance appraisal. For instance, that there was almost 50% overprovision of space for classes of 0-45 pupils, and 8% underprovision for classes of 46-50 pupils. That the statutory 2% minimum daylight factor was not met at most points in teaching spaces (whether this is a design 'failure' or a failure in performance standards is an interesting question); that teaching areas only accounted for 50% of the total area; and that teachers' judgements as to how central they were in the school was related to distance from the main entrance (but upper floors and stairs destroyed this relationship). In a way, an appraisal such as this raises more questions than it answers; but without doing this it would be futile to consider writing performance specifications based on the responses and resources of the users of the system.

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Fig. 1 Conceptual model of the building/environment/activity/objectives/resources system.

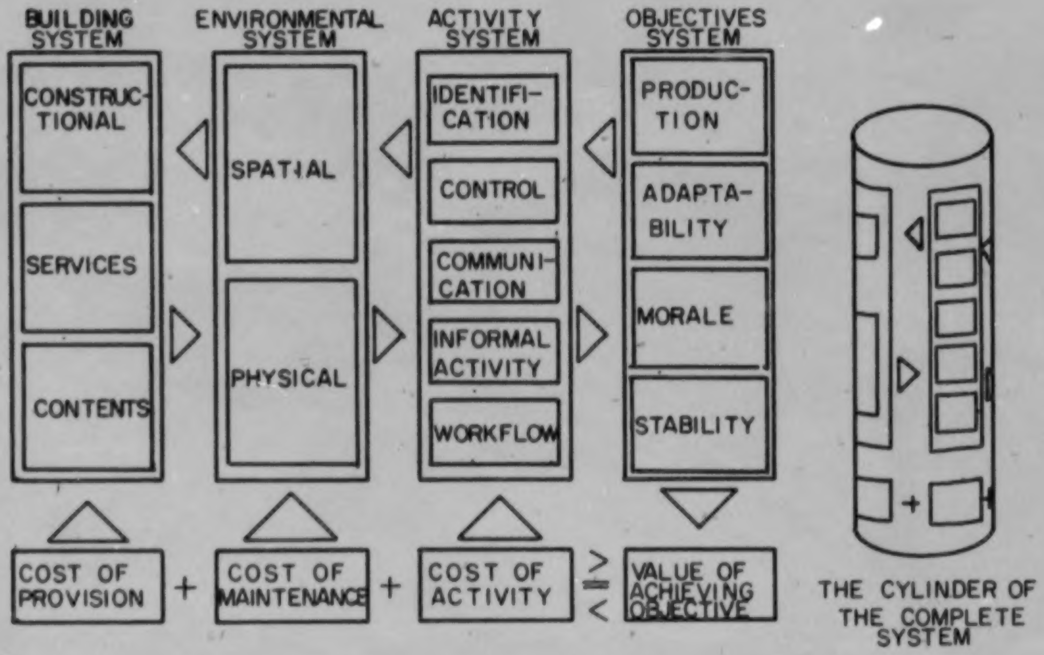
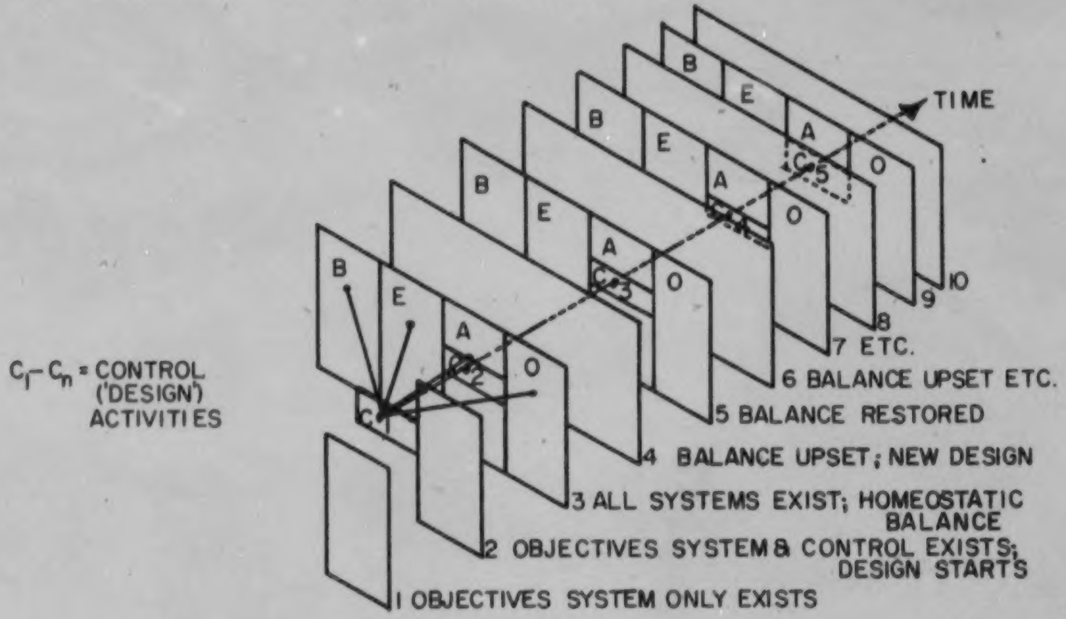

BUILDING SYSTEM
CONSTRUCTIONAL
SERVICES
CONTENTS
ENVIRONMENTAL SYSTEM
SPATIAL
PHYSICAL
ACTIVITY SYSTEM
IDENTIFICATION
CONTROL
COMMUNICATION
INFORMAL ACTIVITY
WORKFLOW
OBJECTIVES SYSTEM
PRODUCTION
ADAPTABILITY
MORALE
STABILITY
COST OF PROVISION
+
COST OF MAINTENANCE
+
COST OF ACTIVITY
≥
=
<
VALUE OF ACHIEVING OBJECTIVE
+
THE CYLINDER OF THE COMPLETE SYSTEM

Fig. 2 Development of the system over time.


TIME
B
E
A
O
C1
C2
C3
C4
C5
$C_1 - C_n$ = CONTROL ('DESIGN') ACTIVITIES
1 OBJECTIVES SYSTEM ONLY EXISTS
2 OBJECTIVES SYSTEM & CONTROL EXISTS; DESIGN STARTS
3 ALL SYSTEMS EXIST; HOMEOSTATIC BALANCE
4 BALANCE UPSET; NEW DESIGN
5 BALANCE RESTORED
6 BALANCE UPSET ETC.
7 ETC.
8
9
10

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A Systems Approach for the Evaluation of Performance of Buildings in Design Process

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Buildings are man-made physical systems which are essential, in one way or another, for almost all activities in the society. The worth of a building is some combined measure of its performance in the functional, technological, economic, perceptual-aesthetic and sociological contexts. However, most of the work done in the evaluation of performance of buildings has been directed to specialised aspects within isolated contexts and is often limited to particular types of buildings. There is a need for considering the evaluation of overall performance of a building within the design process framework of a building as a system. This paper is intended to be a step towards the fulfillment of this need.

In the design process, the concept of value system that forms the basis of performance specifications and criteria; synthesis of building scheme which specifies the form, materials and construction methods; and operations on information are briefly discussed. The value system is systematically analysed into criteria and constituent measures which in turn are shown to be functions of design parameters and performance variables of a building scheme. The evaluation process starts with the performance ratings at the level of constituent measures and successively integrates them into a single measure of the overall worth of the building design.

Les bâtiments sont des systèmes physiques faits de main d'homme qui, d'un façon ou d'une autre, sont essentiels pour presque toutes les activitiés de la société. La valeur d'un bâtiment est une certaine mesure composée de sa performance dans les contextes fonctionel, technologique, économique, esthétique et sociologique. Pourtant, la plupart des études faites pour évaluer la performance de bâtiments se sont dirigées vers des aspects spécialisés à l'intérieur de contextes isolés et se sont souvent limitées à des types particuliers de bâtiments. Le besoin se fait sentir d'une évaluation de la performance totale d'un bâtiment à l'intérieur du cadre du traitement d'un bâtiment comme système. Cette communication a l'intention d'être un pas vers la satisfaction de ce besoin.

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Ont été brièvement discutés dans le traitement du projet le concept de système de valeurs qui forme la base des spécifications et des critères de performance, la synthèse d'un schème de construction qui spécifie la forme, les matériaux et les méthodes de construction, et les opérations d'information. Le système de valeurs est systématiquement analysé en critères et mesures composantes qu'on montre comme étant eux-memes des fonctions des paramètres de projet et des variables de performance d'un schème de construction. Le processus d'évaluation commence avec les estimations de performance au niveau des mesures composantes et les intègres à la suite en une unique mesure de la valeur totale du projet de construction.

Key Words: Building design, design process, evaluation, performance, systems approach, user requirements, value system.

1. Introduction

The ever-increasing complexity of building needs, the vast amount of resources required to fulfill these needs and the available scientific and technological potential have produced an unprecedented interest in the policy, planning and design decisions in building industry. The responsibility of the decision makers in this field, be they national policy makers, real-estate developers, architects, engineers or construction managers, has greatly increased. There is emerging interest in the systems approach to the entire building process which has led to research in design methods, performance criteria and user's needs. Numerous design methodologies have been proposed and almost all of those stress the importance of evaluation in design.

In this paper a critical look at the building design process is attempted and a method for evaluation of the overall worth of a building design is proposed. The concepts of need, resources, value system and performance criteria, and information are defined and briefly discussed. The value system is systematically analysed into criteria and constituent measures which in turn are shown to be functions of design parameters and performance variables. The proposed evaluation process starts with the performance ratings at the level of constituent measures and successively integrates them into a single measure of the overall worth of the building design.

2. Building Design Process

John Dewey (6)[3], Hall (10), Asimov (3), Alexander (1), Archer (2), to name a few, have expressed a variety of views on rationalised design methods. These views have been analysed, abstracted, compared and discussed at various conferences (11), (7), (13). Page (14) has pointed out that there seems to be one common point of agreement among the design theorists and that is that analysis, synthesis and evaluation are basic operations in systematic design and can be recognised at all levels of the design process.

One recognises an overall operational sequence in building activity. These operations can be grouped chronologically under phases like feasibility study, preliminary design, detailed design, planning for construction, construction, occupation and evaluation under use. The scope of the following discussions is limited to operations before detailed design phase. Figure 1 shows the operations and their mutual relationships in the feasibility study and preliminary design phase. The terminology and concepts involved are briefly discussed below.

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[3] Figures in parentheses indicate the literature references at the end of this paper.

2.1 Need

A design problem situation generally begins with the realisation of a need which as defined by Hall (10) as a state of tension or imbalance in the environment which tends to discharge in behavior aimed at relieving the tension or restoring the balance.

2.2 Resources

In the most general sense resources are the human, physical and financial capabilities of the society to fulfill its needs and wants. Resources may be broadly classified into long term and short term. Long term resources include the overall educational, technological and natural resource potential of the nation; the political, economic and social systems and their anticipated states in the future. Short term or immediate resources include the available capital, time, talent, technology and natural resources. A building project is conceived in the framework of long term resources, consumes short term resources but ideally contributes to long term resources.

2.3 Value System

The value system of a society is a coherent collection of commonly accepted beliefs and attitudes, and logical truths that provide the bases of evaluation and choice in situations of conflict. One distinguishing feature of the value system is that its development always involves some subjective reasoning.

The value system for buildings can be developed within five contexts that are identifiable because of their respective emphases. These contexts are functional, technological, perceptual-aesthetic, sociological and economic. Blachère,(4) by grouping the performance requirements as physiological, psychological, sociological and economics,has suggested an alternate set of contexts.

Each context has a corresponding set of general criteria. Figure 2 shows the break up of technological context into its criteria;namely,physical realisability, safety, serviceability and durability. Each criterion corresponds to some characteristics of the building (or its sub-systems) that could be called the constituent measures of that criterion. For example one constituent measure of safety of a building would be the structural strength compared with anticipated loads on the building structure. This is normally represented by the safety factors, load factors or probabilities of failure. Another constituent measure of safety is ductility, which represents the reserve deformation and energy absorption (and thus warning) before collapse, an important attribute when the structure is subjected to seismic loads. Similarly there are constituent measures of safety against fire and other hazards in the building.

2.4 Information

Information is the medium of design activity. The entire design process may be looked upon as a series of operations on information. From the realisation of need for a building to the production of construction documents the information is received, recalled, collected, improved, created, converted and transmitted, not essentially in the same order. Unlike the value system information is mostly objective in nature and is obtained empirically by observation or experimentation.

Information in a building design situation covers a very large area and can be classified in various ways (15).

Amongst the major problems with information in a design situation are those of definition, existence, and quality. It is important to seek definition of the nature of information required for a particular design problem. Poor or questionable information search at the earlier stage in design can effect all the subsequent questions raised in the design process and thus have negative effect on the whole process. Major research effort may be needed to seek information that is non-existent or insufficient in quantity. Often resource constraints make such research unfeasible and one has to resort to conservative suppositions. The quality of information is a function of its validity and reliability and can be improved by increasing the sensitivity and reliability of the means and methods by which the information is acquired.

The character of randomness may exist in many types of information in building technology for example loads, material properties and building component dimensions. Probabalistic analysis is required to correctly account for randomness. While there is considerable research in this area, especially in structural engineering, the mathematical difficulties of the probabalistic models and lack of reliable information have so far prevented widespread application of such approaches in building industry (9).

2.5 Performance Requirements

As shown in figure 1, at the very outset of the design there is an interaction between the needs, value system and resources that results in the idealised goals which are the statements of what the building should ideally accomplish. Rightful aspirations as well as checks on extravagant desires while determining our goals come from the value system and long range resource constraints. The idealised goals are transformed to "attainable" goals by immediate resource constraints, pertinent organised knowledge and experience from similar design projects. These goals can then be translated into performance requirements. The value system in the form of context and criteria weightages and relevant information play an important role in this translation of goals into performance requirements. It is to be noted that since the performance concept is based on requiring desirable and preventing undesirable attributes of a building (17), the performance requirements reflect our value system and can be grouped under the various criteria and contexts.

2.6 Development of Alternate Schemes

A scheme is a proposed building design that, when fully developed, can be described within each context and their respective criteria and constituent measures.

The following assumptions about the nature of a scheme are made:

1. Each scheme has a corresponding set of environmental factors like the acting loads, design parameters like the structural spans and story heights and some associated constants like the mechanical properties of materials.
2. A set of values of design parameters defines a design within that scheme.
3. There is a set of performance variables, preferably in one to one correspondence with performance requirements, and it is possible to state a performance variable as a function of some design parameters, environmental factors and constants.
4. The values of a performance variable satisfy the constraint represented by the corresponding performance requirement.
5. The constituent measures within performance criteria are constructed by one or more performance variables.

Considering the state of the art in building, the above statements are very idealistic. With the possible exception of technological and economic context a great deal of basic research (e.g. environmental psychology) and development work (e.g. anthropometrics and spatial-functional requirements) is needed to make it possible for us to define a scheme, in as much detail as implied in the above assumptions.

3. Evaluation of the Overall Worth

In order to choose from among various alternate schemes we must be in a position to evaluate the alternate schemes. Because of interdependence, lack of dimensional homogeniety and quite often the inverse relationship between various criteria in buildings (e.g. safety and economy) it becomes necessary to have a single measure of overall worth of a scheme in order to compare and choose from two or more alternate schemes. The following paragraphs outline an approach by which the overall worth of a scheme can be obtained. It is important to point out that the sole objective of this evaluation approach is to rank the schemes in comparison with one another rather than to give absolute evaluation to every scheme.

3.1 General Remarks

The proposed method and the implied assumptions are described in the following paragraphs:

1. One step judgement on the worth of a scheme is likely to suffer from arbitrariness, subjectivity and bias. In order to reduce this likelihood the proposed approach is characterised by a spreading out of evaluation activity to a large set of constituent measures within the largest possible set of criteria that are well focused on distinct aspects of their corresponding contexts. Each scheme is rated on every constituent measure and these ratings are then combined, as shown in figure 3, to get the overall worth of a scheme.

2. The evaluation of a scheme is a multidimensional scaling problem. The overall worth of a scheme is a function of its ratings on each criterion individually as well as the ratings on groups of mutually dependent criteria. However, it is assumed that the criteria are independent. This results in addivity of values (5) which means that the overall worth of the scheme is a sum of the ratings of a scheme in different contexts which in turn is a sum of the ratings on various criteria and so on.

3. In the technological and economic contexts most of the performance attributes of the building are quantifiable in the sense that there are measurement techniques and mathematical models that would reliably predict the value of a performance variable corresponding to a given set of environmental factors. For example there are performance requirements associated with the criterion of serviceability. One of the constituent measures of serviceability is deformation of building structure under load. A series of performance variables, consisting of deflections at specific points, can be mathematically modelled as functions of design parameters of the scheme such as structural geometry, material properties, end conditions and environmental factors such as loads, temperatures, settlements, etc. Thus if the anticipated deflections in a scheme can be calculated from mathematical models or experimentally determined from scale-model studies, and compared with the corresponding performance requirements (e.g. maximum allowable deflections which are based on technological as well as perceptual-aesthetic considerations), one has a quantitative basis for rating the scheme on the particular constituent measure of deflections.

In the perceptual-aesthetic and sociological contexts there are no well-defined and widely-accepted design parameters, environmental factors and performance variables for buildings. Neither are there any definitive and empirically substantiated models relating man and buildings in these contexts. While there is extensive work done in psychometrics and comparative judgement (8), (16) the application of this work to man-building relationships has remained considerably underdeveloped. It is proposed that in the absence of objective scales for the rating of a scheme in perceptual-aesthetic and sociological contexts, subjective preference ratings by experts as well as representative groups of the future users of the building should be obtained. In this regard MacGillivray's (12) work on the aesthetics of junkyard screening is a good example of the use of available scaling techniques like pair comparisons on preference rating scales.

The proposed approach consists of the following three steps:

3.2 Step I: Establishment of Context, Criteria and Constituent Measure Weightages

We are concerned with weightages at three levels namely contexts of the total value system, criteria within the contexts, and constituent measures within the criterion. Each one of a set of weightages will have a non-negative value less than 1 and their sum will be equal to 1 indicating that the successive partitioning from contexts to criteria to constituent measures is exhaustive. In the following discussion some general guidelines are proposed for the establishment of their values.

Context Weightages:

Context weightages indicate the relative importance of functional, technological, perceptual-aesthetic, sociological and economic contexts and thus are direct representation of our value system as regards the buildings. In committing oneself to such a set of weightages the following two approaches may be taken:

1. Good architecture shows no preference for one context at the cost of another.

2. The relative importance of contexts is dependent upon the specific nature of the building, current priorities of the society and resource constraints.

It is suggested that the former approach is the ideal, and latter the reality. We must move away from the ideal as little as possible in order to meet the constraints of reality. In other words we must attach equal and the highest degree of importance to each context unless the practical aspects of the problem very definitely demand a bias towards any of the contexts in comparison with the others.

Criteria Weightages

Every context has a corresponding set of criteria. Some criteria are more important than others. Each criterion weightage will be denoted with two subscripts identifying the context and the criterion. For the choice of criteria weightages the following general guidelines are proposed:

1. The importance of a criterion should be proportional to the sum of absolute values of the positive consequences when a scheme is rated very high (close to 1 on a 0-1 scale) on this criterion and the negative consequence when the scheme is rated very low (close to 0 on a 0-1 scale).

2. When enough information is not available to warrant imbalance in criteria weightages, equal weightages may be assigned. This is similar to Laplace's argument that since nothing is known about the future all the states of nature may be considered as equiprobable.

3. The criteria weightage within a context that in itself has received high weightage must be dealt with more carefully as compared to the criteria weightages under the context that has been rated low.

Constituent Measure Weightages

Every criterion has a corresponding set of measures which stand for the considerations that together represent the attributes of the system that the said criterion is supposed to measure. Each weightage will be denoted with three subscripts identifying the context, criterion and the constituent measure. The guidelines for establishing the relative weightages of constituent measures are similar to those for criteria weightages.

3.3 Step II: Evaluation of the Scheme on Constituent Measures

At the present stage of development of this approach the following two methods are proposed to construct 0-1 intervals for rating of schemes on constituent measures:

1. Consider the case when it is possible to assign quantitative value x to performance attributes (positive for desirable, negative for undesirable) of the scheme related to the measure on which the scheme is to be rated. A rating of 1 can be assigned to the scheme that corresponds to the highest value of x, denoted by X_1. Similarly a rating of 0 or close to 0 can be assigned to the scheme with the lowest value of x, denoted by X_0. The other schemes can then be rated by adopting a characteristic function between X_0 and X_1.

   Assuming that we are dealing with a phenomenon that is consistent in its overall nature within the range established by X_0 and X_1 we can conclude that the characteristic curve between 0 and 1 will be strictly monotonically increasing. Theoretically there can be an infinite number of such curves. If we have a definite basis for doing so we can select a specific curve representing a specific measure. Otherwise it would be a good policy to adopt a straight line between 0 and 1.

2. In cases where the performance attribute can best be described by a statement we can define 0-1 interval by the description of least and most desirable states of the scheme. A characteristic curve can then be adopted between 0 and 1. Once the statement describing the scheme with respect to the constituent measure is located on this interval, the corresponding rating can be obtained from the assumed characteristic function.

3.4 Step III: Calculation of the Overall Worth

The objective of this step is to combine the ratings on the constituent measures to obtain the overall worth of the scheme.

The following notation is introduced:

i, j, k : subscripts identifying constituent measure, criterion and context respectively
n, m, N : numbers of constituent measures within a criterion, criteria within a context and contexts respectively
r : rating of the scheme on a constituent measure
w : weightage
R : overall worth of a scheme.

Based on the assumption of addivity of worths, the expression for the overall worth of a scheme can be derived in the following form:

$$R = \sum_{k=1}^{N} w_k \left[\sum_{j=1}^{m_k} w_{(j,k)} \sum_{i=1}^{n_{(j,k)}} w_{(i,j,k)} \cdot r_{(i,j,k)} \right]$$

Since

$$\sum_{k=1}^{N} w_k = \sum_{j=1}^{m_k} w_{(j,k)} = \sum_{i=1}^{n_{(j,k)}} w_{(i,j,k)} = 1$$

and

$$0 \leq r_{(i,j,k)} \leq 1$$

it can be shown that R will have its values between 0 and 1. It is important to point out that since the ratings were obtained by mutual comparison of the alternate schemes, the only significance of the numerical value of R is in final ranking of one scheme in comparison with others and thus making the final choice.

4. Summary and Conclusions

A method is proposed to rank the alternate building schemes by evaluating their overall worth as regards their anticipated performance under environmental factors to which they would be subjected in use.

Value system for buildings is successively analysed into contexts, criteria and constituent measures which represent one or more performance requirements. A scheme is characterised by design parameters and some constants and has a set of performance variables which correspond to the set of performance requirements that are provided by the value system. Environmental factors are part of the information and yield specific values of performance variables for a scheme. A scheme can be rated on a constituent measure by comparison of extreme values of performance variables with the corresponding performance requirements in that constituent measure. Assuming the independence of criteria, the ratings on constituent measures are combined to obtain the overall worth.

This study has, more than anything else, pointed out the need for further work towards:

1. Evaluation of the performance of buildings in use and its comparison with the evaluation of anticipated performance of a scheme during the design stage.

2. Development of widely acceptable criteria, constituent measures and performance requirements in the perceptual-aesthetic and sociological contexts to a comparable degree of refinement as in the technological and economic contexts.

3. Development of more specific bases for the establishment of context, criteria and constituent measure weightages.

4. Investigation into the time characteristics of the value system as represented by the performance requirements and relative weightages of various criteria. The designer will be best served if he has some rational basis for predicting the value system under which his building will function in future.

5. Acknowledgements

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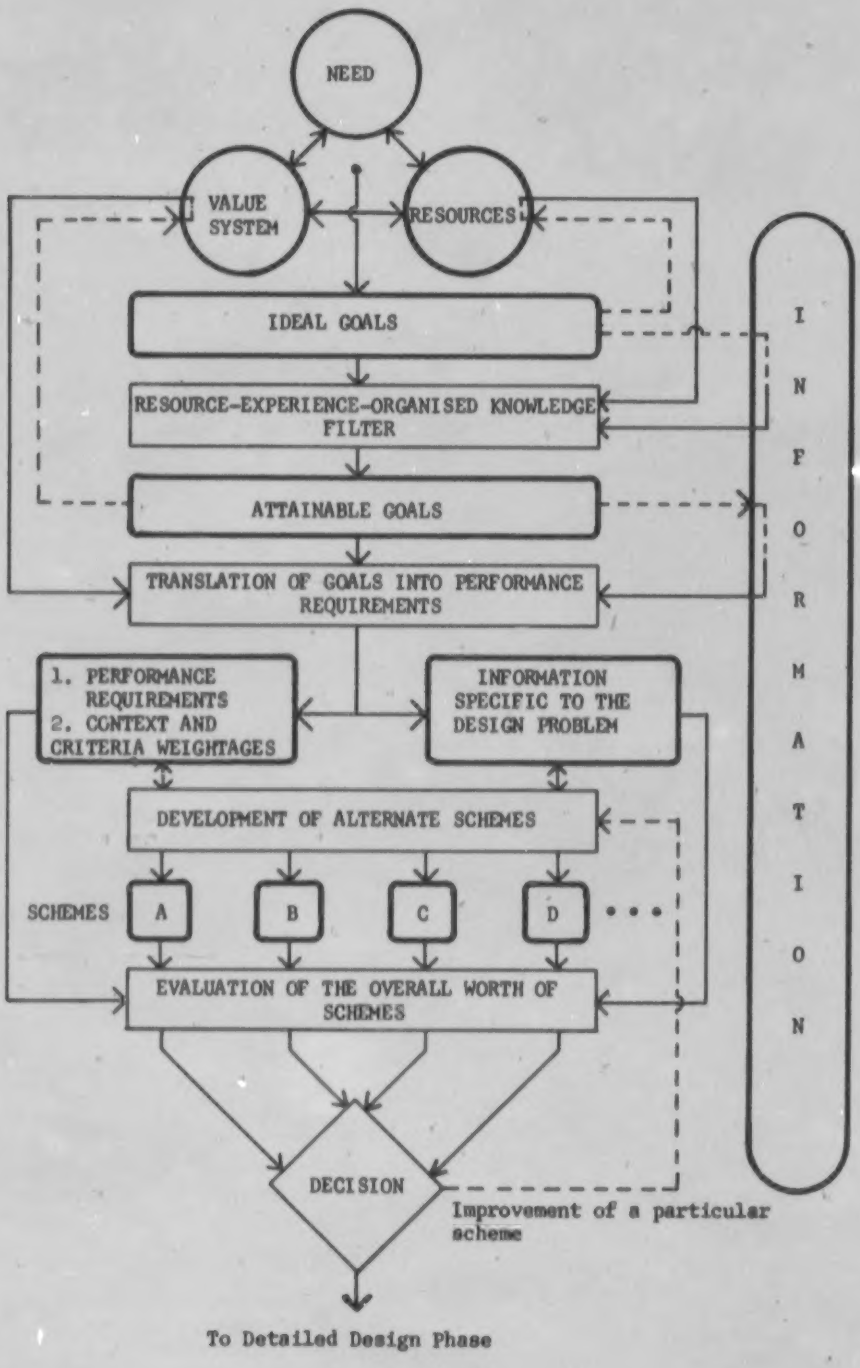
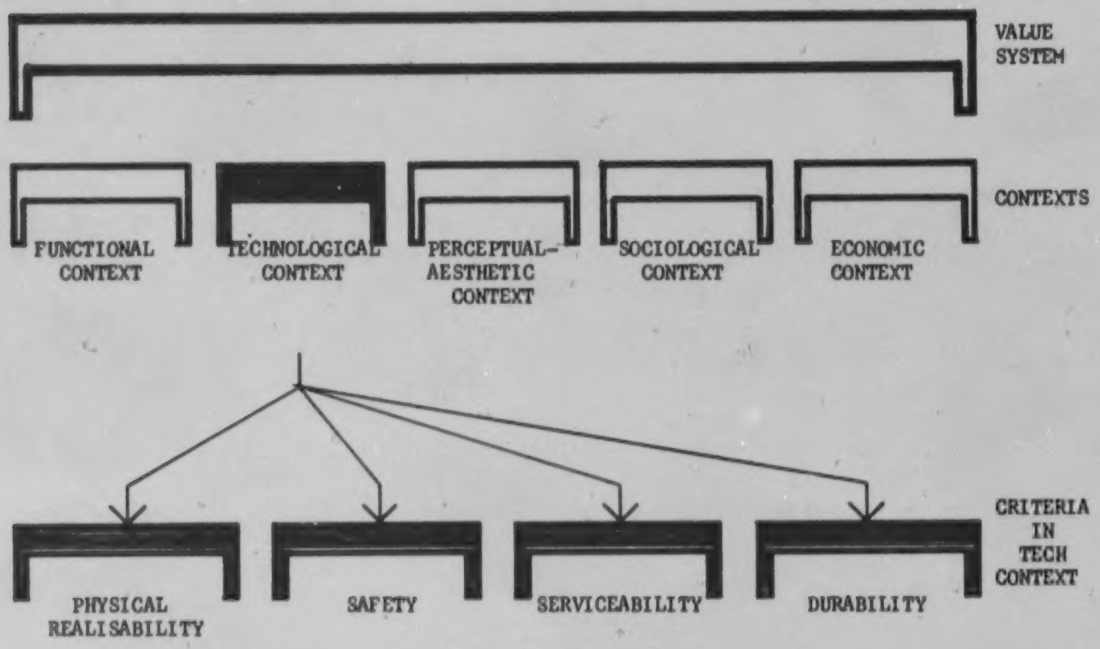

NEED
VALUE SYSTEM
RESOURCES
IDEAL GOALS
RESOURCE-EXPERIENCE-ORGANISED KNOWLEDGE FILTER
ATTAINABLE GOALS
TRANSLATION OF GOALS INTO PERFORMANCE REQUIREMENTS
1. PERFORMANCE REQUIREMENTS
2. CONTEXT AND CRITERIA WEIGHTAGES
INFORMATION SPECIFIC TO THE DESIGN PROBLEM
DEVELOPMENT OF ALTERNATE SCHEMES
SCHEMES
A
B
C
D
EVALUATION OF THE OVERALL WORTH OF SCHEMES
DECISION
Improvement of a particular scheme
INFORMATION
To Detailed Design Phase

FIGURE 1. BUILDING DESIGN PROCESS


VALUE SYSTEM
CONTEXTS
FUNCTIONAL CONTEXT
TECHNOLOGICAL CONTEXT
PERCEPTUAL-AESTHETIC CONTEXT
SOCIOLOGICAL CONTEXT
ECONOMIC CONTEXT
CRITERIA IN TECH CONTEXT
PHYSICAL REALISABILITY
SAFETY
SERVICEABILITY
DURABILITY

CONSTITUENT MEASURES IN TECHNOLOGICAL CONTEXT

*DURATION AND EASE OF CONSTRUCTION

*NEED FOR SPECIAL MATERIALS AND METHODS

*NEED FOR SPECIAL SUPERVISION AND INSPECTION

*CLIMATIC EFFECTS ON CONSTRUCTION

*
*
*
*
*
*

*STABILITY

*STRENGTH

*DUCTILITY

*SAFETY AGAINST FIRE AND OTHER HAZARDS

*SAFETY OF MECHANICAL AND ELECTRICAL EQUIPMENT

*SAFETY DURING CONSTRUCTION

*
*
*
*

*DEFORMATIONS DUE TO SERVICE LOADS

*DEFORMATIONS DUE TO EXCEPTIONAL LOADS

*TEMPERATURE MOVEMENTS

*MOVEMENTS DUE SETTLEMENTS

*RESPONSE CHARACTERISTICS UNDER DYNAMIC LOADINGS. NATURAL FREQUENCIES ETC.

*
*
*

*DURABILITY OF INTERIOR FINISHES UNDER SERVICE CONDITIONS

*DURABILITY OF EXTERIOR FINISHES UNDER CLIMATIC EXTREMES

*DURABILITY OF CONNECTIONS UNDER REPEATED LOADS

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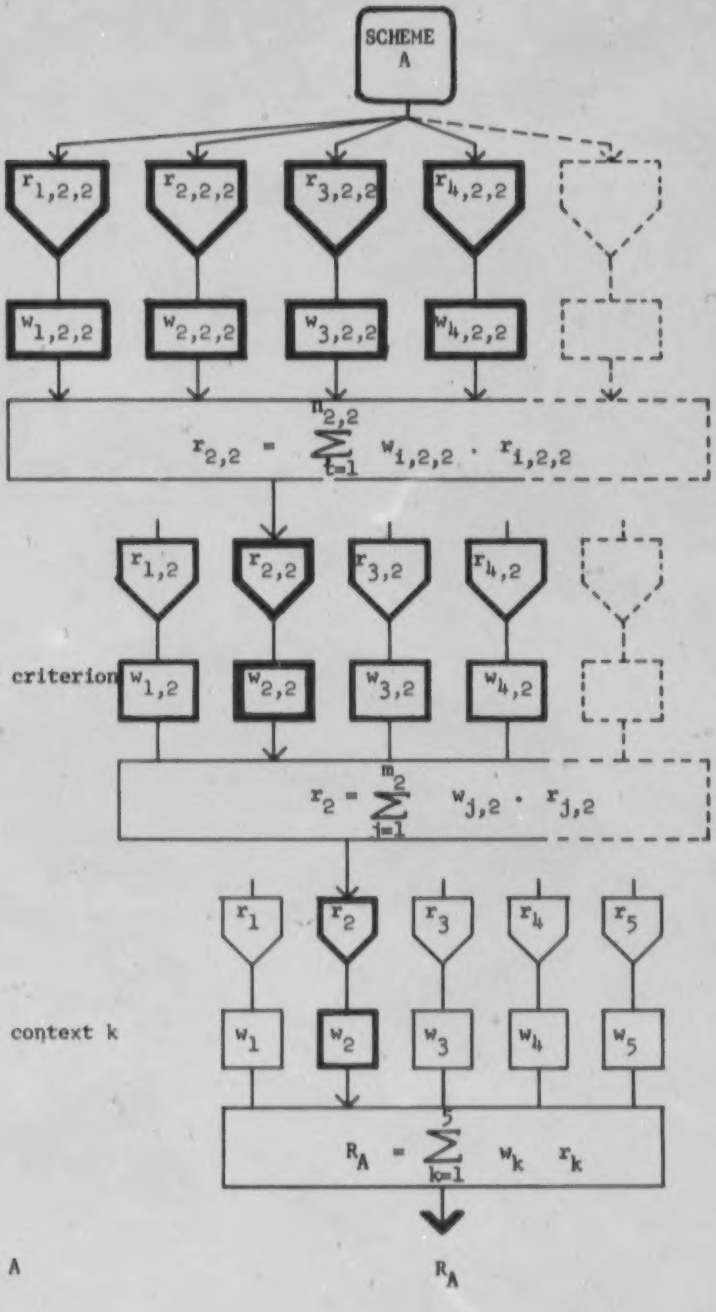
FIGURE 2. CRITERIA AND CONSTITUENT MEASURES IN THE TECHNOLOGICAL CONTEXT


SCHEME A
$r_{1,2,2}$
$r_{2,2,2}$
$r_{3,2,2}$
$r_{4,2,2}$
$w_{1,2,2}$
$w_{2,2,2}$
$w_{3,2,2}$
$w_{4,2,2}$
$r_{2,2} = \sum_{i=1}^{n_{2,2}} w_{i,2,2} \cdot r_{i,2,2}$
$r_{1,2}$
$r_{2,2}$
$r_{3,2}$
$r_{4,2}$
$w_{1,2}$
$w_{2,2}$
$w_{3,2}$
$w_{4,2}$
$r_2 = \sum_{j=1}^{m_2} w_{j,2} \cdot r_{j,2}$
r_1
r_2
r_3
r_4
r_5
w_1
w_2
w_3
w_4
w_5
$R_A = \sum_{k=1}^{5} w_k \ r_k$
R_A

$r_{i,j,k}$ = rating of scheme on constituent measure i in criterion j in context k

$w_{i,j,k}$ = relative weightage of constituent measure i in criterion j in context k

$w_{j,k}$ = relative weightage of criterion j in context k

w_k = relative weightage of context k

R_A : the overall worth of Scheme A

FIGURE 3. TYPICAL RELATIONSHIPS OF RATINGS AND WEIGHTAGES IN THE EVALUATION OF OVERALL WORTH OF A SCHEME.

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

An Innovative Approach for Building System Analysis and Design

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The intent of this paper is to introduce a new computer program formulated to aid in the evaluation of performance of building systems and components. The new program is designed to define, within a range of possibilities, the scope of future innovation in building systems and components necessary to improve their performance for the user and their profitability to the manufacturer.

Le but de cette communication est d'introduire un nouveau programme d'ordinateurs formulé pour aider à l'évaluation de performance de systèmes et d'éléments de construction. Le nouveau programme est conçu pour déterminer, dans les limites de la gamme des possibilités, la portée d'innovations futures en systèmes et éléments de construction nécessaires pour l'amélioration de leur performance vis-à-vis de l'usager et leur avantage pour le manufacturier.

Key words: Building system analysis; design; innovation; mathematical model; predictive technique.

1. Introduction

In view of the present and projected demand for housing, the level of achievement in housing construction is not very satisfactory. Alarming signs, like the declining input/output ratio, indicate that steps must be taken soon to increase productivity. In addition to an increased volume of housing, its cost must be kept within the budget limitations of the people for whom it is produced.

Effort is being intensified at national levels, at the construction industry level, and at the level of the individual house builder to produce a larger volume of low-cost housing. In order to make important decisions on a more accurate basis, it has become obvious that planning for this endeavor requires a new programmatic mechanism with specific performance criteria. These performance criteria must take the form of numerical statements.

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[1] Architect and Structural Engineer

Analysis and evaluation of the performance of existing building systems and components has now become essential in order to lay a basis for assessing future requirements and to guide the development of new designs. The technical progress that results from this procedure of analysis, evaluation and prediction is perhaps the main factor in the growth of the economy as a whole, as well as the increased productivity and economy of the housing industry.

2. Performance Profile

The most widely used form of building evaluation has consisted of analysis of building costs. The simplest criteria for building cost are similar to those in estimating (unit price, cost/sq. ft. or cost/cu. ft.). Their usefulness depends directly on the exactness of available information. These criteria do not, of course, evaluate a building as a constructional system at all. It should be noted that in the past, cost standards have been changed more rapidly than performance requirements. Moreover, many methods of building evaluation disregard the important fact that construction results from numerous activities characterized by the following basic stages of the total building process:
-the process for determining user requirements for operation and maintenance;
-the process of architectural and engineering design;
-the process of producing building materials;
-the process of building assembly.

A large number of usually complex relationships within a building must be considered simultaneously if the appropriate solution is to be found. Under these circumstances, it appears inappropriate to make complex evaluation of a building on cost criteria alone, which by their generality, seem to be suitable just for the first stage of the building process. With the necessary introduction of human factors in housing schemes, the situation becomes then more complicated and almost hopeless unless mathematical means and computers are used to handle it.

At present, the general tendency is to intensify architectural programming and simplify the building assembly to achieve the highest performance at the lowest possible cost. This results in obviously conflicting demands for variations and flexibility on one hand and economical efficiency of the building production and assembly on the other.

Two possible solutions lie in either developing new technologies, or selecting a certain number of housing types or building components to satisfy certain functional variations and requirements of the client.

The first possibility is more likely. In order to determine the technological and design changes necessary a new predictive characteristic must be incorporated in our programmatic mechanism. This will effect the conceptual and detail stage of the design process, the component technology, and assembly.

Few companies that design and manufacture building components can afford to be concerned with these trends and consequences, if they are even aware of them. Those who will be concerned with long-range planning and the need to employ predictive techniques probably:
-operate on a larger than municipal scale...i.e.: regional, national, or international;
-employ a large number of people and deal with high production volumes;
-have made large capital investment (exceeding the $1 million figure);
or:
-represent the building industry itself or its important parts.

The performance profile of any housing program (i.e.: of any documented effort to build a house) is fully dependent on the prime consideration we or the interested party wishes to establish. In general terms the performance profile shows how concerned we are with (a) function, (b) economy, (c) safety and (d) comfort of the particular building. We must also be aware of the fact that there is a difference between the performance desired, the performance designed, and that actually achieved. This means that the final performance can be affected by each stage of the total building process and as such must be assessed.

3. New Model

Every enterprising individual or organization strives for optimal solutions. Unless examples exist or some appropriate standards have been established, optimal solutions can only be derived from careful analysis and comparison of alternatives. Specific data for comparison must be gathered to measure, count, test and retest objectives, designs, or activities.

A procedure of collecting data through testing has an implicit potential both to evaluate the object under study, and to refine the set of criteria developed as the unifying base for comparison. Changes in technology and changes in the analytical model may necessitate changes in this original criteria.

In most cases criteria are mathematically formulated to provide a rational basis for decision making. The mathematical model, as we call it, of the given process is then represented by a series of simple equations arranged:

-to describe the building process and its operations step by step;
-to show the consequences of changed priorities and decisions made by the user each time new data is introduced;
-to show the consequences of the introduction of new technical data.

The method of mathematical programming has been used for feasibility studies, preliminary designs, cost estimates and cost control programs. However, all these programs have been devised to solve current problems. In order to meet future building needs, to predict their extent and to develop new technologies, technical progress within the building industry will have to be subject to other considerations than the profit/loss ratio (considerations of comfort, and consumer preference) and will have to be better planned. Many existing computer programs could be modified for this purpose, however a new mathematical model may prove to be more appropriate. The main objectives to be achieved are:

-to initiate more comprehensive long-term planning and design and
-to accelerate the future operations of the component manufacturer with the possibility of adjusting these to temporary demands and short-term pressures.

With the backing of one large Canadian organization such a program is now in the process of development and testing. For obvious reasons its details will not be available for some time. Nevertheless the following information may serve as an indication of the extent of work required to complete this computer program.

The creation of a program to promote improvement and to define the scope of future innovation will have to be started with the identification of parameters characterizing precisely:

-existing socio-economic conditions, standards, codes (range of products on the market, minimal floor area requirements, etc.);
-technical trends of the industry in the past five years (growth of productivity, industrialization, etc.);
-the company itself with respect to the parameters above;
-the pace with which the company wishes to proceed with changes (every two or three years).

To synthesize the appropriate ranges of future optimal solutions requires that this program must include all the complex criteria at the outset.

The complex criteria to be used for evaluation of existing house designs or construction processes and prediction of performance with technical innovation in mind must determine:

-fundamental relationships of a qualitative and quantitative nature among the stages of the total building process (qualitative = positive or negative; quantitative = numerical value, extent) and
-Interrelationships within these stages, i.e.: among the individual considerations or steps of procedures.

Comprehensive information and data for this new model will have to be provided in order to assure that a sufficient number of criteria are developed. These criteria relate obviously to the performance profile of the whole building and its stages.

Respecting the stages of the building process, the data to be processed must in general deal with:

- scale of operations--number of units, total volume or floor area;
- adaptability--multiplication of functions;
- extent of possible expenditure, loans, cost of operations, maintenance and insurance, extent of returns, interest rates, time scheduling;
- consideration of locality with respect to climate and resources of manpower and materials;
- legal aspects--use of building codes, limitations affecting the building, etc.;
- geometry of a building--sizes, elevations, numbers;
- space allocations and relationships, envelope characteristics, fenestration;
- building system classification, fundamental structural characteristics;
- variations in consumer choice;
- considerations of materials and their arrangements;
- characteristics of services and installations;
- components, characteristics and numbers, steps assuring the required quality of construction;
- production in general, extent of the output, time limits, characteristics of machinery for production material handling and assembly, extent of the input of capital investments, basic characteristics of the labor content, production and assembly.

In principle, the new model of the total building process (i.e.: program, design, component production and erection) is represented by a system of two equations for each, tabulated to form eight interconnected zones, with feedback introduced intentionally:

- to improve performance of the components of the building and of the building as a whole in terms of precisely stated requirements;
- to detect via the mathematical indicators the most likely needed innovations.

Multiple recording of the findings from earlier analysis and comparisons is another feature of the model before the necessary future changes in component design and manufacture can be identified. The decision to innovate is based on the effectiveness of the proposed changes with respect to:

- labor costs;
- scheduling of building operations;
- their duration;
- the extent of additional investment connected with the proposed innovation.

Characteristics used to propose future changes in component manufacture and design are so far very few and general in nature. Among others, the numerical instructions can delineate ranges of desired:

- organizational changes;
- changes of technology and desired modernization of production facilities;
- new capital investment;
- sequence and extent of operations;
- material and its physical properties;
- performance of machinery;
- labor content in the process of applying the innovation;
- limitations;
- further information, research, etc.

It is assumed that people familiar with the project under study will be able to use these instructions as guidelines for changes, modifications, and new development. The model will not provide direct answers; it will only indicate a reasonable range of possibilities the company can choose from.

Although the model will not do any architectural planning, it can evaluate in principle and provide a set of guidelines to make the architectural design more efficient from technical and economic points of view.

Despite the given explanation, there are many questions left unanswered. It is too early to say what effect the mathematical model would have on the whole house-building industry. The role of housing in the national economy, social progress and social well-being has been recognized. Then, what sense does the idea of securing economical efficiency and unmatched superiority make, if we all know the hardship of improving technical performance of our buildings and maintaining their costs on the one hand, and frustrating and disrespectful easiness of land speculation and other shortcomings of our system on the other. It appears to be unfair and hard to believe, that the industry itself should carry the burden of social, economical and technical progress.

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A General Overview of Operation BREAKTHROUGH

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Operation BREAKTHROUGH was initiated with the overall objective of increasing housing production by breaking through the barriers which constrain the use of innovative materials and systems in producing housing. Twenty-two housing systems were selected by the Department of Housing and Urban Development (HUD) to participate in the program by erecting housing on selected prototype sites. The Building Research Division of the National Bureau of Standards (NBS) was selected to write performance based criteria and evaluate the housing for HUD. A technical panel formed by the National Academies of Sciences and Engineering is providing HUD with independent advice on the results of the NBS evaluations.

L'opération "BREAKTHROUGH" a été lancée avec le but global de faire brèche dans les barrières qui empêchent l'usage, dès le début, de matériaux, de systèmes et de méthodes innovateurs dans la production d'habitations. Vingt-deux systèmes de bâtiment ont été sélectionnés par le Department of Housing et Urban Development(HUD) pour participer au programme en érigeant des habitations sur emplacements types choisis. La Division de Recherches sur le Bâtiment National Bureau of Standards évalue le logement en utilisant des critères fondés sur la performance, critères développés par HUD. Un groupe d'experts techniques formé par les Académies Nationales des Sciences et des Ingénieurs fournit à HUD un avis indépendant sur les résultats de l'évaluation du National Bureau of Standards.

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[1] Structural Research Engineer

Key words: Department of Housing and Urban Development; housing; industrialized housing; innovative housing; National Academies of Sciences and Engineering; National Bureau of Standards; Operation BREAKTHROUGH; performance; performance criteria.

1. Introduction

In 1949 the United States Congress established the goal of a decent home in a suitable living environment for every American. This goal was reaffirmed in the Housing Act of 1968 with the determination that 26 million housing units would need to be produced in the decade of the 1970's. This will require an annual production rate of about 2.5 million units in the early 1970's and a higher rate in the late 1970's.

Conventional methods have been inadequate to produce housing in the United States at the rate of 2.5 million units. The best prior production effort had been only 2.0 million units in 1950. Production ranged from 1.2 to 1.6 million in the 1960's. It became evident that new methods must be developed to supplement the traditional ones of providing housing in order to achieve increased production. Yet, an increase in production must not be achieved at the expense of a suitable living environment.

It was determined that the Department of Housing and Urban Development (HUD) should take steps to encourage the accelerated development and acceptance of advanced approaches in providing housing. Thus, Operation BREAKTHROUGH was initiated with the overall objective of breaking through the barriers which constrain the use of innovative materials and systems in producing houses. Within this overall objective for Operation BREAKTHROUGH, Harold Finger, the HUD Assistant Secretary for Research and Technology, has outlined [1][2] the following major operational objectives:

- "To develop the means for supplementing our production of housing to assure the supply needed for our total population in the years ahead";
- "To modernize zoning regulations so as to develop improved land use arrangements that provide the living space needed for a good living environment";
- "To develop performance criteria and building code improvements to encourage improved housing systems";
- "To attract into the housing business the architects, the planners, the suppliers, the engineers, the broad range of industrial capacities, financial institutions, management organizations, builders, and developers that have the ability to develop improved housing system approaches";
- "To encourage production and operating arrangements with our labor organizations and with the labor force that makes more effective use of our full labor force (all skill levels) to overcome the already existing and worsening shortage of skilled labor";

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[2] Figures in brackets indicate the reference at the end of this paper.

- "To encourage new techniques and materials";
- "To encourage the development at our State government level of a concern with and a capability for the development of housing based on the improved approaches that are developed in the program";
- "To encourage actions at State and local level that will provide an opportunity for all people to obtain housing where they want it and to live in an environment where a sense of responsibility and satisfaction is encouraged";
- "To seek out innovative and expanded financing mechanisms, recognizing that we may need basic reform in the monetary institutions and regulatory law."

These objectives were aimed at improving the entire housing process rather than just serving as an advance for innovation.

In order to implement the program, proposals were requested from 5000 organizations and over 600 were received. Twenty-two housing systems and eleven proposals for various hardware and software components of housing were selected for contract purposes. Ten prototype sites, now reduced to eight, and one subsite were selected from 218 sites proposed for development.

The 22 BREAKTHROUGH systems vary from component panels to three-dimensional modules. About one-third of the systems use wood structures while the remaining use concrete, metal, or plastic structures. Conventional residential structures use about 75 percent wood construction.

Operation BREAKTHROUGH considers the design of the overall residential community as part of the housing problem. This community design is as much a part of the program as improvements in building design and production process. Thus, eleven site planners were selected out of 82 proposers to design prototype sites demonstrating improved land use, community design, and improved building designs on the prototype sites. Eight site developers were selected out of 65 proposers to manage and be responsible for overall site work. Several planning and design ideas which differ markedly from normal site design have resulted from the design process, and are included in the prototype site plans.

2. Evaluation Base

2.1 Development of the Evaluation Criteria

Many of the housing systems which were proposed for Operation BREAKTHROUGH contained innovations in materials, fabrication, and erection which could not be readily evaluated on the basis of the reference standards in codes. Thus, it became evident that Operation BREAKTHROUGH required technical support to evaluate the housing. The Building Research Division, Institute for Applied Technology, of the National Bureau of Standards, Department of Commerce, has been providing this interdisciplinary technical support [2].

A first step in the technical support program to evaluate innovative housing systems was the development of criteria for the evaluation of such systems on a performance basis. The criteria were prepared by the National Bureau of Standards. Concurrently, the Department of Housing and Urban Development was carefully designing a process for the review of the criteria. In order to assist in the review process the Department of Housing and Urban Development (HUD) requested that the National Academies of Sciences and

Engineering establish a special advisory committee.

The formal procedure finally established for the review process was for the National Bureau of Standards to develop criteria; transmit these to the Department of Housing and Urban Development for review; and finally, for the Department of Housing and Urban Development to transmit them to the Advisory Committee for review.

The Department of Housing and Urban Development issued the criteria to the Housing System Producers for their guidance during the design and development portion of the program. Valuable information was received from their application of the criteria. The criteria were updated and improved on the basis of this information. Finally, during occupancy, significant data are expected from a detailed evaluation program of the performance of the housing systems.

2.2 Philosophy of Evaluation Criteria

The evaluation criteria developed for Operation BREAKTHROUGH were organized in a four-volume document entitled Guide Criteria for the Evaluation of Operation BREAKTHROUGH Housing Systems. The four volumes were for (1) multifamily high-rise (four-stories and greater in height), (2) multifamily low-rise (less than four-stories in height), (3) single family attached, and (4) single family detached housing systems. Each volume of the evaluation criteria was organized in accordance with the matrix shown in figure 1, where the numbered columns in the matrix correspond to attributes and the lettered row corresponds to built elements. Thus, for example, under Section H-5 (H is plumbing, the built element, and 5 is acoustic environment, the attribute) of the criteria, one would expect to find a performance statement for noise generated by plumbing.

Each performance statement consists of a requirement, one or more criteria, test, and a commentary (optional) and follows a consistent format throughout the document. The requirement is a statement of general performance in terms of the housing system. The criterion is a statement of factors to be controlled or measured in the housing system. The test is a statement of how the factors in the criterion are to be evaluated in the housing system so that compliance with the level of performance intended in the criterion can be determined. The term "test" is used in its broadest sense to connote the means for demonstrating compliance, and can thus refer to engineering computation and analysis, prior documented experience, or physical simulation. If there are American Society for Testing and Materials tests or other standard tests which are applicable, these are referenced.

The final item which makes up a complete performance statement in the BREAKTHROUGH Criteria is a commentary. This is not a necessary component of the performance statement. However, since Operation BREAKTHROUGH is an experimental program and since these criteria represent a translation of the most advanced state of the art, it was considered desirable to state the intent and the degree of confidence in the performance levels or test methods specified as well as the significance of the factors to be controlled and evaluated, in terms of the housing system.

The criteria differ technically from existing building codes both in language and in scope. First, codes tend to be prescriptive in nature and component oriented. On the other hand, the BREAKTHROUGH Criteria are, so far as the present state of the art permits, performance based and systems oriented. Secondly, codes are concerned primarily with the areas of health and safety. The BREAKTHROUGH Criteria cover not only health and safety, but also liveability and durability. This broader scope was considered necessary because BREAKTHROUGH aims at producing housing that is both safe and of improved quality to satisfy user needs.

In the area of health and safety, the Criteria were written to achieve at least that level which is intended in present codes. In the areas of liveability and durability a base level was used that could be obtained through a conscientious execution of moderate-level conventional construction. Conventional housing solutions automatically provide certain levels of liveability and durability, even though these are not specifically called for in the codes pertaining to housing. However, with innovative systems, there is no implicit, time-proven guarantee that these same levels of liveability and durability will be obtained.

3. Evaluation Process

Design drawings and specifications have been submitted for review by the 22 housing systems producers at intervals of preliminary, 25 per cent, 95 per cent, and final stages of completion. At each of these progressive stages, the National Bureau of Standards is reviewing the designs, attempting to predetermine those details that will be acceptable, those that must be tested further, and those that are suspected of being unacceptable.

A considerable amount of BREAKTHROUGH evaluation has already taken place, and a number of physical tests have been carried out or are underway. Before recommendations are made to the Department of Housing and Urban Development concerning the acceptability of any system, the system will be thoroughly evaluated and, where required it will be thoroughly tested. In addition to this, the system's performance on the prototype sites will be evaluated.

The National Bureau of Standards is acting as the focal point for all testing and evaluation. Other public and private laboratories and consultants are also being used. After thorough evaluation of a system, the National Bureau of Standards will submit the results along with recommendations to the Department of Housing and Urban Development for review and subsequent transmission to the Advisory Committee Technical Panel of the National Academies of Sciences and Engineering [2].

4. Advisory Function of the National Academies of Sciences and Engineering

A Technical Panel was set up for review and evaluation purposes by a joint Advisory Committee to the Department of Housing and Urban Development (ACHUD) of the National Academies of Sciences and Engineering [3]. Two aspects of the BREAKTHROUGH program are being reviewed; first, the evaluation base to be used for judging the adequacy of the housing systems; and second, a review of the NBS evaluation reports to determine acceptability of each housing system.

The Technical Panel will advise HUD regarding the acceptability of any housing system after it has been thoroughly briefed by the NBS on the evaluation results, has had an opportunity to study the test reports, and, when appropriate to do so, has inspected the prototypes. Activities of the Technical Panel will culminate in reports which will advise HUD that the system should or should not be accepted.

Once the Department of Housing and Urban Development has received recommendations on each of the 22 housing systems from both the National Bureau of Standards and the Academies, HUD will exercise its own judgment as to whether it will approve the systems. By the time the BREAKTHROUGH program is completed, each system is expected to have been thoroughly documented and evaluated with regard to its performance in use.

5. References

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Built Elements			*Attributes*								
			STRUCTURAL SERVICEABILITY	STRUCTURAL SAFETY	HEALTH AND SAFETY	FIRE SAFETY	ACOUSTIC ENVIRONMENT	ILLUMINATED ENVIRONMENT	ATMOSPHERIC ENVIRONMENT	DURABILITY/TIME RELIABILITY (FUNCTION)	SPATIAL CHARACTERISTICS AND ARRANGEMENT
			1	2	3	4	5	6	7	8	9
	STRUCTURE	A									
INTERIOR SPACE DIVIDERS	WALLS, INTER-DWELLING	B									
	WALLS, INTRA-DWELLING	C									
	FLOOR-CEILING	D									
EXTERIOR ENVELOPE	WALLS, DOORS AND WINDOWS	E									
	ROOF-CEILING, GROUND FLOOR	F									
	FIXTURES AND HARDWARE	G									
	PLUMBING	H									
	MECHANICAL EQUIPMENT, APPLIANCES	I									
	POWER, ELECTRICAL DISTRIBUTION, COMMUNICATIONS	J									
	LIGHTING ELEMENTS	K									
	ENCLOSED SPACES	L									

Figure 1 Guide criteria matrix

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

Philosophy and Scope of Structural[1] Performance Criteria

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In the program entitled "Operation BREAKTHROUGH", the U.S. Department of Housing and Urban Development is supporting and guiding the development of industrial housing systems and encouraging innovation in housing technology. Evaluation criteria that were developed by the Building Research Division of the National Bureau of Standards' Institute of Applied Technology will be applied to all "Operation BREAKTHROUGH" housing systems. This paper presents the philosophy for the development of Structural Performance Criteria, which are derived from the user requirements of safety, activity support, low maintenance cost, absence of stress and anxiety and visual acceptability. One example is quoted to illustrate the form of these criteria, which comprise three groups: strength, stiffness and rigidity, and resistance to local damage.

Dans le programme intulé "Opération BREAKTHROUGH", HUD (U.S. Department of Housing and Urban Development) entretient et guide le développement de systèmes industriels d'habitation et encourage les innovations technologiques en ce domaine. Des critères d'évaluation développés par la Division des Recherches sur la Construction du Bureau National de Standards, l'Institut de Technologie appliquée, seront utilisés pour tous les systèmes d'habitation de l'Opération BREAKTHROUGH. Cette communication présente la théorie pour le développement de critères de performance de la construction, qui découlent des demandes de l'usager, pour la sécurité, les supports d'activité, le coût réduit d'entretien, l;absence de tension et d'anxiété et l'esthétique. Un example est cité pour illustrer la forme de ces critères: force, raideur et rigidité et résistance aux détériorations locales.

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[1] This paper has been submitted to the American Society of Civil Engineers for consideration for publication in the Journal of the Structure Division Proceedings.

[2] Structural Research Engineer and Assistant Chief respectively, Structures Section.

Key words: Deflection; load capacity; performance criteria; performance evaluation; structural engineering; stiffness; strength; structures; user requirements; vibration.

1. Introduction

Advances in building technology lead to the introduction of new and unproven design concepts and material applications. As a result of such innovations, some recently-developed building systems defy analysis by traditional engineering principles. Frequently, the adequacy of these systems cannot be evaluated using existing building codes and design standards.

Some of the difficulties in the evaluation of these systems can be overcome by the introduction of performance criteria which are not specifically related to particular design concepts or material solutions. The Building Research Division of the Institute for Applied Technology, National Bureau of Standards, has worked for several years to initiate and develop performance criteria as a supplement to building codes and design standards, and as a guide to designers and developers of innovative building systems. These performance criteria are now being applied in the Department of Housing and Urban Development's Operation Breakthrough to determine and certify the adequacy of industrialized housing systems.

2. Development of Performance Criteria

The performance of any structural element or subsystem must be defined in terms of its function. Since the function of a building is to serve the needs of its users, performance criteria must be derived from user needs.

The objects of all user needs and wants cover a spectrum ranging beyond necessities to amenities, all of which can never be satisfied within given economic constraints. Thus user requirements must be selected which represent those user needs which should be satisfied in any particular case.

Some user requirements are obvious. For instance, it is obvious that the occupants of a building should be protected against death, injury or financial loss caused by structural collapse. In other cases, the selection of user requirements is difficult and user needs are not well understood. For instance, we do not completely understand how much motion and acceleration can be tolerated in a building before discomfort or insecurity is experienced.

On the basis of user requirements, performance requirements can be determined. Performance requirements state those attributes which the built environment must have in order to satisfy user requirements. For instance the user requirement to limit excessive motion in a building results in the performance requirement of adequate stiffness and rigidity.

A performance requirement can only be implemented when compliance with the requirement can be objectively determined. The determination of compliance requires the statement of the performance in terms of measurable quantities. Such a statement is a performance criterion. It should be noted that the quantities should be measurable and that the methods, by which the quantities are to be measured, should be stated. For instance, criteria for structural stiffness will state deflection limits. In order to make deflection limits quantitatively measurable it is necessary to state the magnitude and duration of loads under which these deflections must not be exceeded and testing procedures by which compliance with the criteria can be determined for any particular structure.

The steps in the previously - discussed methodology are shown in the flow chart below:

USER NEEDS

USER REQUIREMENTS

PERFORMANCE REQUIREMENTS

PERFORMANCE CRITERIA

These steps were used to develop performance criteria.

In Operation Breakthrough each performance criterion first gives the requirement for which it was derived, then the criterion is stated, quantitatively wherever possible, then the method is stated by which compliance with the criterion may be evaluated. Finally a commentary explains the purpose, derivation, use, and limitations of the state of knowledge on which the criterion was based. This format not only presents a criterion but also explains the purpose and intent of the criterion thus enabling the developer of an innovative system to satisfy the intent in a way which may not have been envisioned when the criterion was developed.

It is not the aim of this paper to discuss methods for evaluating performance but it is evident that a criterion can only be used if a method of evaluating compliance with the criterion is available.

The following discussion is limited to structural performance criteria.

3. Structural Performance Criteria

The following user requirements, stated in very broad categories, were identified:

1. Safety
2. Activity support (e.g., floor deflections should not cause a table to be unsteady)
3. Acceptable level of maintenance cost
4. Absence of stress and anxiety (e.g., no discomfort shall be caused by excessive vibrations induced by footsteps).
5. Visual acceptability (e.g., the appearance of a wall-ceiling joint will not be objectionalbe because of excessive deflection).

Table 1 shows the performance requirements that were derived from these user requirements.

Table 1. Relationship Between User Requirements and Performance Requirements for Structural Attributes.

User Requirements	Performance Requirements for Structural Attributes

Safety	Strength
Activity Support	Stiffness and Rigidity
	Resistance to Local Damage Under Service Conditions
Acceptable Level of Maintenance Cost	Resistance to Local Damage Under Service Conditions
Absence of Stress and Anxiety	Stiffness and Rigidity
	Resistance to Local Damage Under Service Conditions
Visual Acceptability	Stiffness and Rigidity
	Resistance to Local Damage Under Service Conditions

It can be seen from Table 1, that essentially three categories of performance requirements were identified:

1. Requirements for strength
2. Requirements for stiffness and rigidity (static and dynamic)
3. Requirements for resistance to local damage under service conditions.

Several criteria are necessary to quantify each of these requirements. The actual performance level stated in these criteria is in each case selected to satisfy the user requirements. The titles of the performance criteria, which were developed for each category of performance requirements, are listed in Table 2.

Table 2. Structural Performance Criteria

Requirements	Titles of Criteria
Strength	Load Capacity -Extreme Loads Sustained Loads Repeated Loads Catastrophic Loads
Requirements	Titles of Criteria
Stiffness and Rigidity	Vertical Deflections Horizontal Deflections Story Drift Vibrations
Resistance to Local Damage	Structure - Foundation Interaction Interaction Between Structural Elements Volume Changes of Structural Elements Incidental Occupancy Loads (impact, concentrated loads)

4. Scope of Performance Criteria

The criteria listed in Table 2 cover many aspects of performance not considered in present design standards and building codes. With respect to strength, present standards usually specify load capacity and some aspects of sustained-loads effects. Repeated loads, except those causing high cycle fatigue, are not considered in building design and none of the U.S. design standards or codes contain provisions for catastrophic loads such as vehicular collisions, construction accidents and service-system explosion.

With respect to stiffness and rigidity, present standards consider vertical deflections and in a few instances horizontal deflections and story drift. None of the standards contain provisions for vibrations.

In the area of resistance to local damage there are very few provisions in present standards; however, some of the attributes required by the criteria are implicit in structures designed in accordance with good engineering practice.

These additional requirements are necessary if performance criteria are to be independent of specific design concepts and material solutions. Many attributes which are implicit in traditional systems may not be present in untried innovative systems. For instance, we know that stiletto heels will not punch through floors that have been used in the past. Thus our design standards confine themselves to the requirements for deflection and load capacity. However it is conceivable, that some innovative system using stress-skin construction, which would meet all the deflection and load-capacity requirements of present design standards, could suffer serious damage when subjected to the compressive stress and perimeter shear imposed by stiletto heels. Another case in point is the requirement for repeated-load capacity. While we know that structures presently in use perform in a manner acceptable to the users, it is conceivable that an innovative and untried system may be weakened below the acceptable strength level or suffer large permanent deformations under the cumulative effect of many cycles of load application.

A similar case could be made for vibrations, impact resistance and many other attributes required by the criteria.

5. Example of Performance Criteria

One of the criteria listed in Table 2 is stated below:

Load Capacity - Extreme Loads

The structure or any portion thereof should not fail during its service life under a load smaller than the following:

(a) $1.4D + 1.7L$
(b) $0.9D + 1.3W$
(c) $0.9D + 1.45E$
(d) $1.1D + 1.3L + 1.3W$
(e) $1.1D + 1.3L + 1.45E$
(f) $0.9D + 1.7Q$

Where D = Service dead load
L = Service gravity live load
W = Service windload
E = Service earthquake load
Q = Service soil and hydrostatic load

If the load capacity of a system is evaluated on the basis of a single specimen or a sample of several specimens, the ratio of measured load capacity to required load capacity should be such that there should be at least 95 percent probability that the structure in service will have a load capacity not less than the required load capacity, and the least credible load capacity should be adequate to insure that no structure would fail at a load lower than any combination of unfactored service loads. If load capacity is determined by calculation, the load capacity in (a), (d) and (e) should be multiplied by $(1 + 1.5v)$, and the load capacity in (b), (c) and (f) should be increased by multiplying the service loads, other than the dead load, by $(1 + 1.5v)$, where v represents the best possible estimate of the coefficient of variation of the load capacity of a given structural system.

Evaluation: Structural Analysis and/or Physical Simulation

Service loads, stated in the cited criterion, are maximum loads that have a recurrence interval equal to the service life of the structure. In the absence of sufficient statistical information, design loads currently stipulated by codes in conjunction with the working stress method of design are taken as service loads.

The load combinations, stated under (a) through (f) in the criterion, represent loading conditions which are deemed by professional consensus in the U.S. to have a suitably low probability of being equaled or exceeded.

The quantity $(1 + 1.5v)$ accounts for strength variability and depends on the properties of the structural material, the quality of workmanship and the system used. In the case where the variation in load capacity of a population of structures follows approximately a normal distribution, the requirement of an overcapacity of $(1 + 1.5v)$ times the required capacity would mean that approximately 95 percent of that population of structures would have at least the required load capacity.

After stating the criterion itself, the method of evaluation is stated. In this case, because the criterion relates to the overall structure the evaluation method is stated in rather broad terms. However, additional criteria are needed to define "physical simulations", which will be discussed in the subsequent paper.

In addition to a statement of the criterion, it is important to explain the intent of the criterion. This is achieved by use of a commentary giving an explanation of the user requirement to which the criterion is related, as well as of the attribute of the built environment which would produce compliance with the criterion. The commentary also explains the origin of the various quantitative limits in the criterion. This explanation of intent could in some instances enable designers to meet the intent of the criterion in a manner not anticipated when the quantitative limits were determined, and thus encourages innovation.

The performance criteria discussed in this paper are now being applied to the evaluation of industrialized housing systems in Operation Breakthrough.

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Philosophy for Physical Simulation Using Performance Criteria[1]

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Physical simulation may be defined as a testing procedure designed to closely simulate the actual structure in order to determine the response of the prototype structure to the loads it is likely to receive during its service life. Criteria for physical simulation include the selection of critical assembly, the consideration of critical load conditions, the allowance, the allowance for the effects of the service life environment and taking account of variability in structural elements and subsystems. The paper discusses each of these criteria in detail, and presents a philosophy.

Le "simulation physique" peut être dèfinie comme un mode d'épreuve conçu pour simuler étroitement la structure réelle dans l'intention de déterminer la réaction du type de structure aux charges qu'elle devra supporter pendant sa période de service. Les critères pour la simulation physique comprennent la sélection de l'assemblage critique, l'examen des conditions critiques de charge et des actions admissibles du milieu pendant l'usage. Ils font aussi état de la variabilité des éléments de structure et des sous-systèmes. La communication examine chacun de ces critères en détails, et présente une théorie.

Key words: Accelerated aging; building systems; extreme loads; performance criteria; performance evaluation; service loads; stiffness; strength; testing; variability.

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[1] This paper has been submitted to the American Society of Civil Engineers for consideration for publication in the Journal of the Structure Division Proceedings.

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1. Introduction

Under the performance concept, criteria may be used in the design and evaluation of a building whatever the type of material used in the various elements.

The physical properties and hence performance vary from material to material and in addition, these properties frequently vary with the manner in which the material is used and with the passage of time.

It follows that evaluation by performance criteria can only be valid if full account is taken of these factors both in the development of criteria and in their application through evaluation.

It is inherent in the performance concept that criteria are independent of, yet able to deal with all materials. In this paper this concept will be taken a stage further by a discussion of the philosophy and scope of an evaluation process. This process is being applied to determine the adequacy of the housing systems within Operation BREAKTHROUGH.

2. Evaluation

Evaluation is the determination of compliance with the performance criteria. It is carried out using one or a combination of the following tools:

analysis
professional judgment
physical simulation.

In most cases, compliance with performance criteria can be evaluated, using recognized concepts of engineering and applied science. For example, the ability of a structure to withstand the racking forces due to a service wind load may generally be evaluated by analysis.

However, consider the criterion that the structure shall not fail after 1000 cycles of loading from 1 Service Dead Load to 1 Service Dead Load + 0.5 Service Wind Load. In this case, evaluation by analysis would frequently not be possible. The evaluation must, therefore, be based on:

professional judgment
or physical simulation

or a combination of simulation and
analysis or judgment.

In some cases, when unproven systems are used the previously discussed methods of evaluation do not provide conclusive information on compliance with performance criteria. In such cases it may be necessary to delay final judgement until the in-service performance of a prototype can be observed.

3. Physical Simulation

When new materials or innovative and untried concepts are introduced, there is frequently no basis for professional judgement and evaluation may require physical simulation through testing.

Physical simulation can be costly and time consuming; thus, it should only be used when analysis and professional judgement are inadequate in themselves.

Physical simulation may be defined as a test procedure designed to closely simulate behavior of the actual structure in order to determine the response of the prototype structure to the loads it is likely to receive during its service life.

Thus, physical simulation corresponds to a service life evaluation. The structural performance criteria set a level of performance applicable for the entire service life of the building. Whereas the passage of time may reduce the level of performance, this performance shall not drop below the levels set by the criteria within the service life defined for the building.

Because building materials, elements and systems generally deteriorate with age, the implication here is that the building shall have a performance which in the early years of its life will probably exceed that called for by the criteria. The margin by which it does so depends on the materials, the system, and, to some extent, uncertainty about both. This is particularly true of innovative systems. Specifically, the structural criteria set a suitable level of performance by criteria in the areas of:

strength
stiffness
resistance to local damage.

These have been discussed in the previous paper. Hereafter one specific means of evaluation is discussed, that of physical simulation, and the criteria for its application.

4. Criteria for Physical Simulation

These criteria call for:

(a) selection of critical subassembly
(b) use of critical loading conditions
(c) allowance for service life environment
(d) consideration of variability in performance.

Each of these four will be discussed in turn:

(a) Selection of Critical Subassembly

The following considerations:

floor span
shear wall location
openings in walls and floors

are just three examples of possible architectural variations in the family of housing units, which should be considered when selecting a structural subassembly for physical simulation. This selection should preferably be conservative and, therefore, take account of, say, the largest floor span to be used or the most adverse arrangement of shear walls. Another case is that of the number and location of openings in walls and in floors. The advantage of a selection of a critical subassembly is that the results offer a basis for conservative judgement. Interpolative judgement can also be used for less critical subassemblies in the use of the system.

(b) Use of Critical Loading Conditions

While not all-inclusive, the following list shows some examples of potentially critical conditions to be considered in the evaluation:

foundation fixity and settlement
construction misalignment and tolerances
time-dependent deformation and volume changes
repeated loading.

In the first of these, where ideal foundation fixity provides a restraint to the structure, the test assembly should allow for the reduced restraint that reasonably could be expected following foundation settlement.

Since fabrication and erection are both subject to dimensional inaccuracies the physical simulation should take account of those forces and added eccentricities of loads which can occur as a result. This practice is similar to that required by design standards for reinforced concrete, an example being the minimum eccentricity of 1/10 the thickness required for concrete columns in the ACI Code [1][3].

The cumulative effect of creep, unrecovered deflections, moisture and temperature on structural capacity must be determined and taken into consideration. For example, these effects in a load-bearing wall panel may serve to magnify the moment in that panel.

Repeated loading due to live load or wind load over the service life of a structure can change the characteristics of structural elements and connections, an example being a reduction of local strength due to fatigue.

It is important to consider the effects of the interaction of various structural elements, a factor which is frequently disregarded in conventional structural analysis. For example, the interaction between the structural frame and non-load bearing partitions may be beneficial in some instances by increasing structural rigidity and detrimental in others by causing local damage in partitions.

The lateral drift due to horizontal loads as well as lateral drift caused by tilting of the structure due to differential foundation settlement, will result in added eccentricities of vertical gravity loads on columns and bearing walls. If a one-story high subassembly is used to simulate the response of a multi-story building, it is important to account for these added eccentricities.

(c) Allowance for Service Life Environment

The material properties of almost all structural elements are affected to some extent by environmental factors such as:

moisture
temperature
ultraviolet light
chemical interaction

It was stated that the required level of performance must be assured throughout the service life of the building. In the evaluation, therefore, consideration must be given to the deterioration of materials and structural elements due to these atmospheric conditions in addition to such effects as user activities and repeated loading. This consideration is particularly important in the evaluation of structural adhesives, which are increasingly replacing mechanical jointing to structural composites. This particular aspect is discussed in reference [2].

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[3] Figures in brackets indicate the literature references at the end of this paper.

(d) Consideration of Variability in Performance

The physical properties of materials, structural elements and structural sub-systems are inherently subject to variation. The factors influencing this variation are numerous and their influence is complex. One need not concern oneself here with these aspects but rather deal with the measured variability as expressed in a frequency distribution. Figure 1 shows the case where the variation in strength of a population of structures follows approximately a normal distribution. In this case the requirement that the mean strength exceed the strength called for in the criterion by 1.5v means that approximately 95 percent of that population of structures would have at least the required strength. The coefficient of variation, v, is the standard deviation divided by the mean for the population. The use of this requirement is appropriate to an evaluation based on analysis. However, it must be noted that the mean strength must account for all the effects of the service life. The coefficient of variation of the strength of a given structure represents the combined effect of variations in material strength, workmanship and control.

For relatively untried materials and concepts, a reasonable allowance should be made for the lack of experience and for unforeseen difficulties by the use of more conservative estimates for v. It should also be recognized that certain structural members require a greater margin of safety than other members. For instance, among a variety of members, there are different strength variabilities, different reliabilities of strength prediction and different consequences of failure. Such considerations explain why concrete columns are recognized to require a greater margin of safety than flexural concrete members.

It was shown that where the mean strength is known with reasonable certainty, the criterion is satisfied if the mean strength exceeds the criterion strength by 1.5v.

The important term here is "known with reasonable certainty."

Consider now that the only basis for evaluation is by testing a number of specimens sampled from a population of structures. The coefficient of variation for this population is v, but the mean value is unknown and is to be assessed. The size of the sample is important to the interpretation of the result.

Figure 2 shows a frequency distribution of strength based on two samplings. The first and flatter curve is for a sample of one and hence its coefficient of variation v' = v. The taller curve is based upon repeated sampling with n specimens. In accordance with sampling theory both distributions have the same mean yet the coefficient of variation of the distribution based on a sample of n is:

$$v'_n = \frac{v}{\sqrt{n}}$$

and is thereby significantly reduced.

Assume that a sample is submitted for evaluation by testing. It is recognized by the evaluator that the test result might be anywhere on the frequency-distribution curve - from extreme left to extreme right. He would therefore judiciously assume that the test strength result is an advantageous one, that is, it falls to the right of the mean in the distribution.

If it is assessed that the mean strength lies 1.5v' to the left of this test result, then only approximately five percent of the population is deemed to be stronger than the test result.

Now one has a reasonable basis for setting the required test strength.

Figure 3 shows that the required test strength is set 1.5v' greater than the mean strength which in turn is set 1.5v greater than the criterion strength. It will be observed that the advantage of the larger sample is a reduction in the overstrength called for in the test.

Without departing too far from what has been discussed, certain aspects of structural behavior should be noted which deserve consideration in an evaluation, but which are not generally considered in conventional design.

To the left of Figure 4 is shown a wall panel subjected to a wind racking load. Within a population of such panels the coefficient of variation of the racking capacity is v.

To the right in Figure 4 several panels are used in "parallel" within a single-story structure. The term "in parallel" is used to indicate that there is joint participation in the resisting of wind loads on the elevation of the building. Where the floor system is capable of acting as a reasonably rigid diaphragm it is obvious that there will be reasonable compatibility in the racking deformations in the panels. Many such wall panels exhibit "a flat top" or ductile portion to their load - deformation response to racking. In this situation, the maximum capacity of the parallel ductile system is reached when all four panels are close to their respective maximum capacities.

In such a case, we have a capacity based upon a sample of four and the appropriate coefficient of variation

$$v'_n = \frac{v}{\sqrt{n}} = \frac{v}{\sqrt{4}} = \frac{v}{2}$$

There are several other cases in which this approach is appropriate.

Turning from the parallel-ductile case, a series-brittle case is considered where wall panels are required to carry vertical loading. In a multi-story building this loading is transmitted through n successive panels to the foundations. Failure of any one panel is deemed a failure in the structure. In such a case, the probability of failure is considerably increased above that of the single-story structure. The preceeding has been a very simplified discussion of a highly complex consideration. Probabalistic concepts, as discussed above, were used in a limited way to evaluate some of the more innovative systems. However, considerably more study will be necessary before the application of these concepts can be extended.

The philosophy for physical simulation discussed in this paper has been applied to determine the adequacy of twenty-two industrialized building systems with the framework of Operation BREAKTHROUGH.

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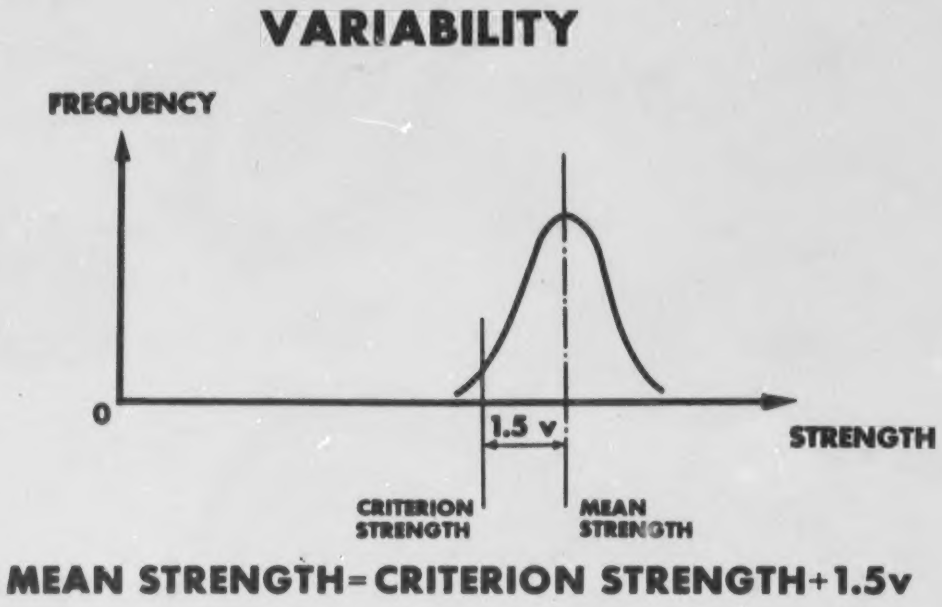
VARIABILITY
FREQUENCY
0
1.5 v
STRENGTH
CRITERION STRENGTH
MEAN STRENGTH
MEAN STRENGTH=CRITERION STRENGTH+1.5v

Figure 1. Relationships between strength variation and required strength.

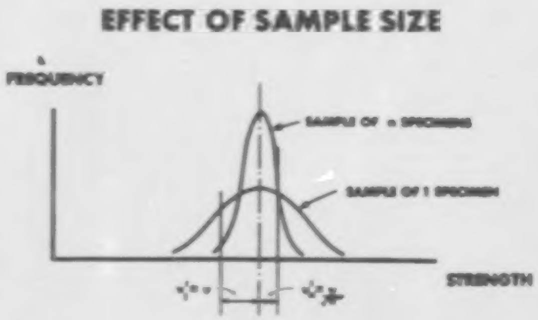

Figure 2. Effect of sample size.

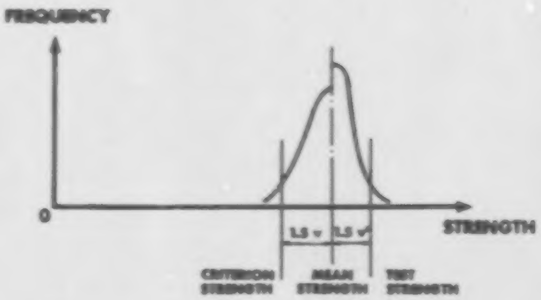

Figure 3. Relationship between test strength and required strength.

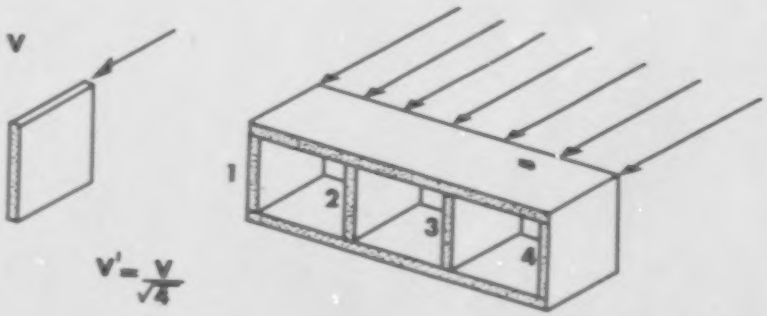

Figure 4. Effect of strength variation of components on the strength variability of the structure.

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Field Testing of Conventional Buildings for Static and Dynamic Deflections

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In order to evaluate innovative materials and systems it is necessary to develop performance criteria for aspects of structural behavior which hitherto have not been considered for traditional materials and solutions. It is reasonable to set levels of performance required by these new criteria so as to achieve a performance which has been acceptable to society over a long period of time. Unfortunately, there is a lack of data on the performance of traditional buildings. This paper describes recent field testing of several conventional buildings in order to confirm the suitability of performance criteria established for static and dynamic deflections within the "Operation BREAKTHROUGH" program.

Pour évaluer des matériaux et systèmes innovateurs, il est nécessaire de développer des critères de performance intéressant les aspects du comportement structural jusqu'ici négligés pour les matériaux et solutions traditionnels. Il est raisonnable de fixer les niveaux de performance requis par ces nouveaux critères pour atteindre une performance que la société considère comme acceptable depuis longtemps. Malheureusement, il y a carence d'informations quantitatives sur la performance des bâtiments traditionnels. Cette communication décrit de récents essais sur place d'une série de bâtiments conventionnels afin de confirmer la justesse des critères de performance établis pour les fléchissements statiques et dynamiques dans le cadre du programme de l' "Opération BREAKTHROUGH".

Key words: Building; design criteria; drift; field test; floor vibration; wood frame.

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1. Introduction

There is currently in the United States a strong trend toward the production of housing by industrialized methods. These methods frequently involve the innovative use of new materials and systems. It is reasonable that the occupant of an innovative housing unit should expect at least that level of performance which he has come to expect from conventional housing.

Attempts to compare innovative housing systems with conventional forms are frequently frustrated by lack of performance data for conventional housing. This can be explained by the fact that conventional housing has evolved over a period of several hundred years on the basis of trial and error. This process has made them generally acceptable in terms of strength, serviceability, and resistance to local damage without the need to quantify this performance. This fact is demonstrated by existing building codes and standards the provisions in which are based implicity on the use of conventional materials and systems. These documents are frequently inadequate for the evaluation of innovative systems for the reasons that the provisions may be inappropriate or provisions may be lacking in areas where it cannot be automatically assumed that the new solution has a performance equivalent to conventional systems.

This paper gives a brief report on two programs of field testing of conventional housing in order to assist the process of establishing performance criteria which might be applied to the evaluation of innovative systems.

Program A was concerned with the performance of housing under horizontal external loads while Program B was concerned with the performance of floors under impact loading.

2. Program A, Performance of a House Under Lateral Loading

2.1 Background

A criterion which is being used[1] to evaluate the performance of houses sets the limit for story drift under service windload at h/500, where h is the height of any floor level above ground. This limit was set in accordance with present professional consensus in the United States with respect to the design of multistory steel and concrete structures. It cannot be determined at the present time whether this limit could be relaxed without causing the occupants to experience discomfort and anxiety under severe wind conditions.

No reliable data are available on the magnitude of drift experienced by buildings of conventional wood-frame construction, which in general, perform in a manner acceptable to the user. The purpose of this investigation was to measure the performance of a new conventionally constructed house under simulated wind loads.

2.2 Description of Building

The building, shown in figure 1, is a conventional two-story wood-frame building with brick veneer over part of the front of the lower story. The lower-story floor is a 4-in concrete slab on grade. Exterior walls consist of 2 x 4[2] wood studs, 16 inches on center, with an interior facing of 3/8 inch thick gypsum board (ASTM C36)[1][3], an exterior facing of 1/2-in thick gypsum sheathing (ASTM C79)[2] and asbestos exterior siding. Upper-level floor construction is 2 x 8 joists, 12 inches on center with 5/8-in plywood subflooring and a 1/2-in gypsum board ceiling. The upper-level ceiling is 1/2-in gypsum board nailed to 2 x 4 joists, which comprise the lower members of roof trusses spaced 24 inches on center. Roof cover consists of 3/8-in 3-ply plywood and asphalt shingles. Interior bearing walls are comprised of 2 x 4 studs, 16 inches on center, and interior partitions 2 x 3 studs, 16 inches on center. All interior walls are covered with 3/8-in gypsum board.

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[1] Guide Criteria for the Design and Evaluation of "Operation Breakthrough" Housing Systems prepared by NBS for U.S. Department of Housing and Urban Development.

Floor plans are shown in figure 2. The lower story comprises a large family room, a bathroom, a bedroom, a garage and two small utility rooms. The upper story consists of a living room with a L-shaped dining room, a kitchen, a bathroom and three bedrooms.

The building has no fireplace or masonry walls in the plane in which the racking load was applied, but some additional lateral rigidity is derived from a backfilled portico with a 4-in concrete slab floor and access stairs butting against part of the front wall at an elevation 2 ft - 10 inches above first-floor level. The four columns shown in figure 1 are doweled to the 4 in. portico slab by a single 1/2-in diameter anchor bolt and do not materially contribute to the rigidity of the building.

2.3 The Test Arrangement

The test setup is illustrated in figure 3. The load was applied by four hydraulic rams, supported on two steel frames which were connected to two concrete blocks, each weighing 5000 pounds. . These blocks were lifted into the proper position by two 10-ton fork lifts. The mounting of the rams to the steel frames and the bolted connection between the steel frames and the concrete blocks permitted the adjustments necessary for proper positioning of the rams.

Deflection measurements were made by 32 displacement transducers (See figure 4), which measured horizontal and vertical displacements near the lower and upper ceiling levels at both exterior walls in three locations (near the two end walls and near the center of the house), as well as the distortion in the plane of one end wall at the lower and the upper story level. One of the displacement transducers was monitored by an X-Y recorder. In addition, all transducer readings were electronically scanned by a data logging system.

2.4 Testing Sequence

Two tests were conducted. In test No. 1 lateral load was applied at the upper story floor level in the short direction of the building and displacements as well as wall distortion were recorded at both the upper and lower story levels.

In test No. 2 lateral load was applied at the upper ceiling level in the short direction of the building and displacements as well as wall distortion were recorded at both the upper and the lower-story levels.

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[2] Nominal sizes in inches (actual dimensions: 1 1/2 in x 3 1/2 in).

[3] Figures in brackets refer to literature references at end of paper.

In both tests load was applied in increments corresponding to wind pressures of approximately 5 psf acting on the entire projected area tributary to each ram location. After each load increment the building was unloaded and reloaded to the next higher load increment.

2.5 Discussion of Test Results

It is beyond the scope of this paper to present all the data. Only the most important data are discussed, namely the horizontal drift and residual drift at the point in the building where maximum drift was recorded. Figure 5 shows a plot of horizontal drift measured near the centerline of the building at location 53 near the upper-level floor line, versus wind pressure. The plot was developed by superposition of the results of tests 1 and 2, combining the proper ram-load levels corresponding to the wind pressures indicated.

For this plot, wind loads were computed in accordance with ANSI Minimum Design Loads [3], using the nominal wind pressure on the vertical projection of the entire building, including the roof. (This is a very conservative approach which corresponds to requirements in Reference 4. The actual wind loads would be less since the resultant force acting on the roof is very small.) It can be seen from this figure that at a wind pressure of 20 psf the drift would be about 1/3 of the allowable drift. Thus, it can be concluded that the building tested would satisfy the drift criteria in most areas of the United States by a considerable margin.

It can also be seen from figure 5 that the residual deflection after completion of the racking tests was only 0.0012 inch.

2.6 Conclusion

The conclusion that can be drawn from this test is that the structure tested has sufficient rigidity to satisfy the drift criterion with a considerable margin.

3. Program B, Performance of Floors Under Impact Loading

3.1 Background

A criterion which is being used[4] to evaluate the performance of floors subjected to normal occupancy loads is as follows:

> "Transient vibrations induced by human activities should decay to 0.2 of their initial displacement-amplitude within a time not to exceed 1/2 second".

The above criterion is based on a limited number of tests on concrete and steel frame structures for commercial use. To date, no reliable data are available that can be used for residential structures. Accordingly, the purposes of this investigation were to determine the dynamic characteristics of conventional wood-frame floors and to develop a method of determining these characteristics.

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[4] Guide Criteria for the Design and Evaluation of "Operation Breakthrough" Housing Systems prepared by NBS for U. S. Department of Housing and Urban Development.

3.2 Scope

Sc The scope of this investigation was limited to vibration tests, induced by impact, of wood-joist floors commonly used in dwelling units. Tests were carried out at the site of a large housing development close to Washington, D. C. which included detached houses of large and medium size, attached houses (townhouses) and multifamily units (apartments).

This test program made no attempt to evaluate numerically the damping characteristics of the floors, nor did it include subjective tests to establish human tolerance against transient vibration.

3.3 Test Program

Seven dwelling units were investigated as shown below:

Detached House (No. 1)	- Furnished	1
	Unfurnished	1
Detached House (No. 2)	- Furnished	1
	Unfurnished	1
Attached House (No. 3)	- Furnished	1
	Unfurnished	1
Apartment	- Unfurnished	1
Total number of dwellings tested		7

To investigate the vibration characteristics of various floors within each unit, five representative rooms were tested in each house and four rooms in the apartment. These rooms included the living room, dining room, kitchen, and one or two bedrooms.

To observe the influence of furniture on the response of the floor, tests were conducted in two identical houses, one furnished and the other unfurnished. The furnished houses were fully equipped with the usual household items including sofas, tables, decorative items, and china in the kitchen and dining areas.

3.4 Test Structures

The houses were of wood-frame construction with either brick-veneer wall or wood siding. The frame structure was constructed of hemlock studs with floor joists of either hemlock or fir. Prefabricated wood trusses were used for the roof framing. For subflooring, 1/2 inch plywood was used in houses No. 1 and 2 and 5/8 inch plywood was used in house No. 3. Schematic drawings of a typical floor layout are shown in figure 6. The direction of spanning of floor joists of the rooms tested is indicated in these figures by a directional arrow (↔).

The apartment was of load-bearing masonry construction with brick veneer. All floor joists were supported by a masonry wall at one end and on a wood stud bearing wall at the other. The floor was constructed of hemlock joists covered with 1/2 inch plywood.

3.5 Variables in Floor Framing

The test floors have five variables: joist size; joist span; joist spacing; subfloor thickness and floor finish. The numerical values of the first four variables and the description of floor finish for each room are listed in table 1. The joist sizes given in the table are nominal dimensions, and the span is the clear distance between the faces of the supports.

3.6 Test Setup and Instrumentation

The test setup is shown in figure 7. It consisted of a weighing bag, a bag-release device mounted on a tripod, and a linear variable differential transformer (LVDT) for deflection measurement.

The bag, filled with sand and lead shot to a weight of 25 pounds, was suspended 3 feet above the floor surface. This test setup produced an impact energy of 75 ft-lb, which was sufficient to induce measureable vibratory motion of the floors.

The LVDT had a range of ± 1.0 inch and was calibrated to read increments of ± 0.0001 inch. Both the loading device and the LVDT were placed as close to the center of the room as possible. The output of the LVDT was recorded by a recording oscillograph equipped with a 600-Hz-response galvanometer.

Each floor was tested under four different test setups as shown in figure 8, the test setups differing from one another in both the location of the LVDT and the impact point with respect to the joist location.

3.7 Test Procedure

The impact load on the floor was induced by dropping the bag. Subsequent to the drop, the bag remained on the floor and vibrated with the floor. To eliminate possible damping provided by the presence of people in the room, the bag-release mechanism was triggered from the adjacent room.

To examine reproducibility of the response of floors, two impact tests were conducted for each test setup. Thus, eight tests were conducted for each floor, two tests for each of the four different test setups.

3.8 Visual Observations During Test

A common phenomenon noted during the tests was a violent rattling of cups and glasses on tables in the dining room and kitchen when the floor was subjected to the impact load. Occasionally, pieces of tableware fell off the table. Then it was noted that a person merely walking across the room caused table settings to rattle. Another phenomenon observed was the vibration of upright furniture, such as bookcases, chests, etc.

3.9 Vibration Data

Typical response to the impact loading is shown in figure 9. It is seen that all initial amplitudes decayed to 20 percent of the initial values within 0.5 seconds. For most floors the initial amplitude decayed to 20 percent of the initial value within 0.2 seconds and tc 10 percent within 0.3 seconds.

The influence of furniture on the response of the floor were examined from the data obtained from the furnished and unfurnished houses No. 1 and

No. 2. Test results showed that no consistent relationship exists between the initial amplitudes of the floors of the furnished and unfurnished houses. However, the vibration of the floors of the furnished rooms decayed faster than those of the unfurnished rooms, which indicates that the presence of furniture does provide some increase in the decay rate; i.e., increase in damping.

Four different types of floor finishes on the plywood subfloor were found in the dwelling units tested. These were: oak strips nailed on subfloor; vinyl asbestos tiles adhered to subfloor; carpet with padding on subfloor; and 1 5/8 in lightweight concrete cast in situ on subfloor.

A comparison of responses of oak strip, tile and carpeted floors of unfurnished houses is shown in figure 10. The data reveal that while no significant difference in the initial impact deflection was observed between the floors finished with oak strip and vinyl asbestos tiles, respectively, a substantial difference in the initial deflection was observed between the floors covered with vinyl asbestos tiles and those finished with carpet. For otherwise similar floors, the initial deflection of the carpeted floors (H3-2) was between 73 and 48 percent of that of the floors finished with vinyl asbestos tiles (H3-3). Of the three finishes, namely oak strip, vinyl asbestos tile and carpets, the carpet provided somewhat greater damping than the other two.

When these three types of finish are compared with the lightweight concrete floors, the latter floor shows greater damping characteristics than the other three.

3.10 Conclusion

The following conclusion may be drawn from the experimental results presented in this report:

> All floors exceeded the level of performance required by the criterion namely that amplitude should decay to 20 percent of its initial value within 0.5 second. In fact, the amplitude of most floors decayed to 20 percent of the initial amplitude within 0.2 second and 10 percent within 0.3 second. This indicates that the wood-joist floors have relatively high damping capacity compared with the referenced criteria. The results further indicated that the damping capacity of wood-joist floors are improved by adding a lightweight concrete finish or carpeting.

3.11 Concluding Remarks

This paper has briefly reported two programs of tests designed to assist the development of performance criteria for housing. This work is being carried out by the National Bureau of Standards on behalf of the U.S. Department of Housing and Urban Development in support of the "Operation BREAKTHROUGH" program.

Under this program, housing is being constructed by 22 systems producers on nine demonstration sites across the U. S. A later part of this program will involve the measurement of user response to the performance of this housing.

This feedback coupled with appropriate field evaluations will offer a valuable supplement to research which is continuing at NBS laboratories in the development of structural performance criteria.

4. References

[1] ASTM C36-68, Standard Specifications for Gypsum Wallboard, 1970 Annual Book of ASTM Standards, Cement, Lime, Gypsum, Part 9, November 1970, pp. 34-36.

[2] ASTM C79-67, Standard Specifications for Gypsum Sheathing Board, 1970 Annual Book of ASTM Standards, Cement, Lime, Gypsum, Part 9, November 1970, pp. 60-61.

[3] A58.1 - 1955, American National Standards Institute, Building Code Requirements for Minimum Design Loads in Buildings and Other Structures, September 1955.

Variables / House	Joist Size (in x in)	Joist Span (ft-in)	Joist Spacing (in)	Subfloor	Type of Wood	Floor Finish
H1(FH1)-1	2 x 10	13-6	16	1/2 in plywood	Fir or Hemlock	Oak Strip[1]
-2	2 x 10	13-6	16		Fir or Hemlock	Oak Strip
-3	2 x 10	13-6	24		Fir or Hemlock	Vinyl Asbestos Tile
-4	2 x 12	20-6	12		Fir or Hemlock	Oak Strip
-5	2 x 10	13-6	24		Fir or Hemlock	Oak Strip
H2(FH2)-1	2 x 10	13-6	16	1/2 in plywood	Hemlock	Oak Strip
-2	2 x 10	13-0	16		Hemlock	Oak Strip
-3	2 x 10	13-1	16		Hemlock	Vinyl Asbestos Tile
-4	2 x 10	12-0	24		Fir or Hemlock	Oak Strip
-5	2 x 10	13-0	24		Fir or Hemlock	Oak Strip
H3(FH3)-1	2 x 10	12-6	16	5/8 in plywood	Hemlock	Carpet
-2	2 x 10	12-2	16		Hemlock	Carpet
-3	2 x 10	12-2	16		Hemlock	Vinyl Asbestos Tile
-4	2 x 10	12-6	16		Hemlock	Carpet
-5	2 x 10	12-6	16		Hemlock	Carpet
A1 -1	2 x 10	14-6	16	1/2 in plywood	Hemlock	Carpet + L.W.C.[2]
-2	2 x 10	11-5	16		Hemlock	Carpet + L.W.C.
-3	2 x 10	11-5	16		Hemlock	Vinyl Asbestos Tile + L.W.C.
-4	2 x 10	10-3	16		Hemlock	Carpet + L.W.C.

[1] Dimension of Oak Strip = 25/32 in x 2 1/2 in

[2] 1 5/8 in Lightweight Concrete

TABLE 1 Details of Floor Framing and Finish

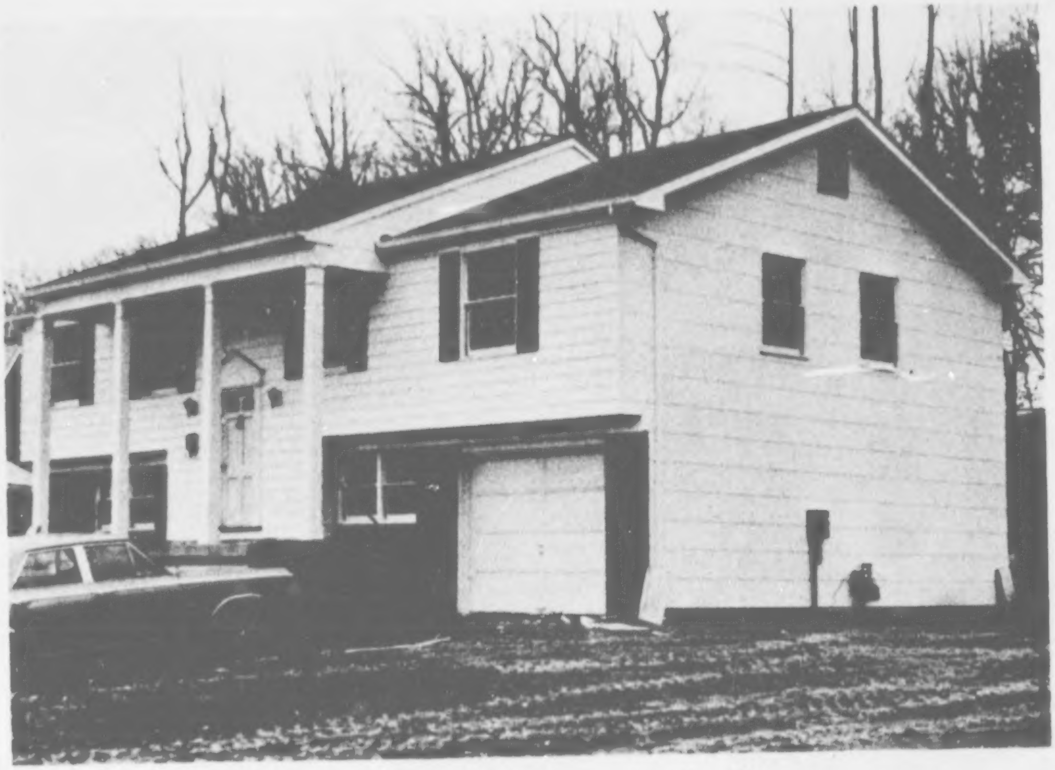
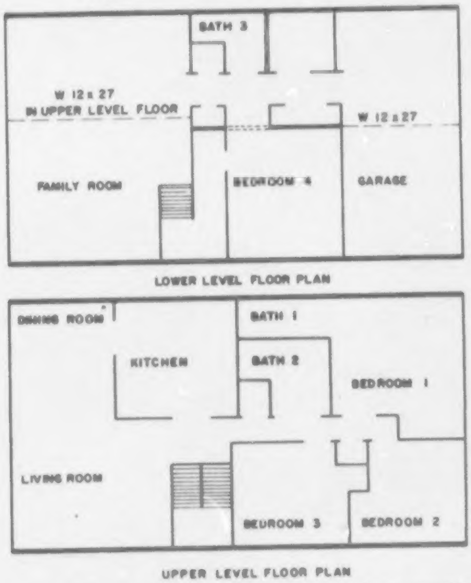


Figure 1 Front View of the House.

Figure 2 Floor Plans.


BATH 3
W 12 x 27
IN UPPER LEVEL FLOOR
W 12 x 27
FAMILY ROOM
BEDROOM 4
GARAGE
LOWER LEVEL FLOOR PLAN
DINING ROOM
BATH 1
KITCHEN
BATH 2
BEDROOM 1
LIVING ROOM
BEDROOM 3
BEDROOM 2
UPPER LEVEL FLOOR PLAN

HEAVY LINES INDICATE BEARING WALLS, THIN LINES INDICATE PARTITIONS

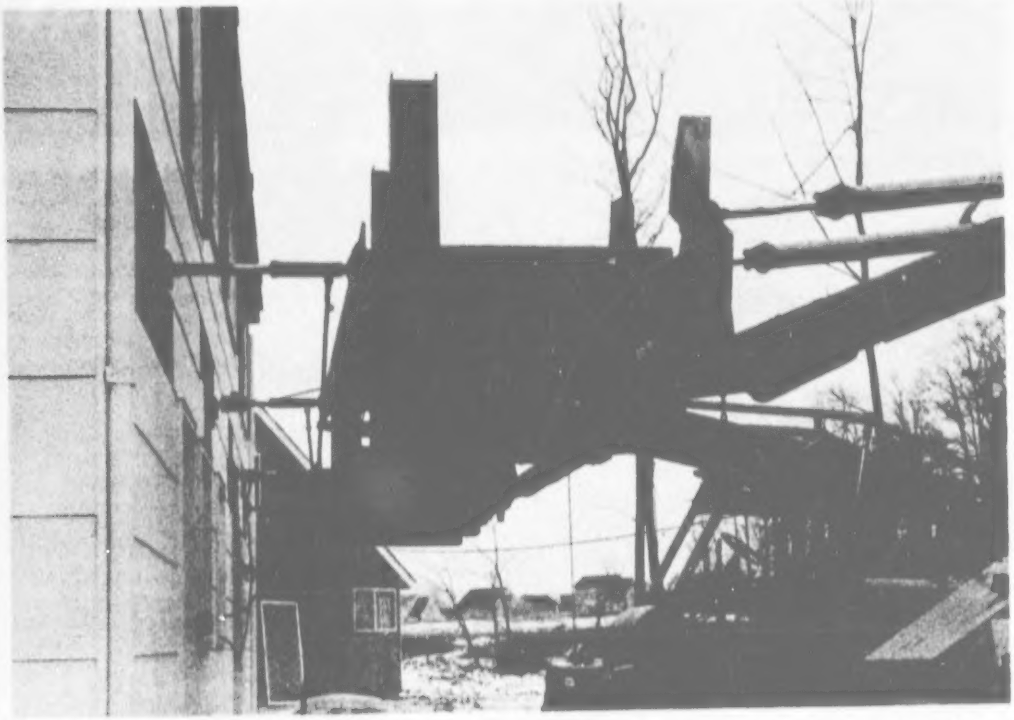
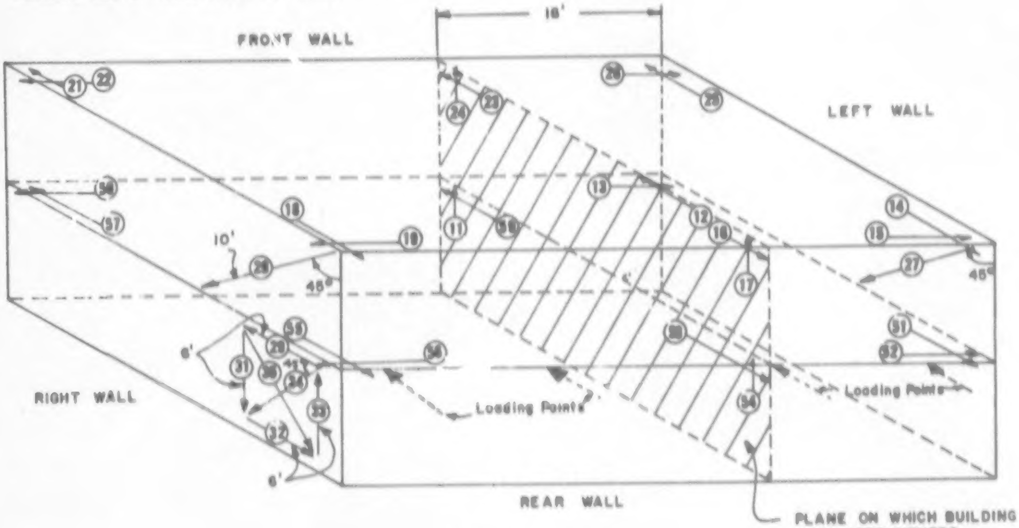


Figure 3 Experimental Setup for Drift Measurement.

Figure 4 Arrangement of Displacement Transducers.

ALL LVDT'S NEAR THE SIDE WALLS, EXCEPT THE LVDT'S
AT THE CENTER VERTICAL PLANE, WERE SET 5.5" BELOW THE
CEILING AND 9" AWAY FROM THE WALL.


18'
FRONT WALL
LEFT WALL
RIGHT WALL
REAR WALL
21
22
24
23
28
25
13
11
12
16
14
15
18
19
10'
45°
27
17
6'
31
32
33
34
Loading Points
Loading Points
PLANE ON WHICH BUILDING WAS INSTRUMENTED

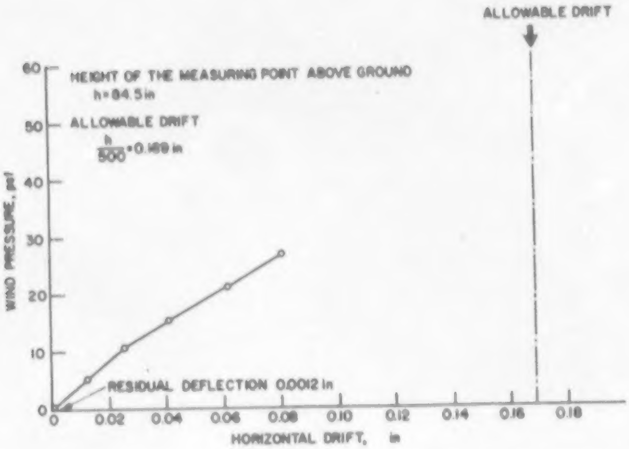
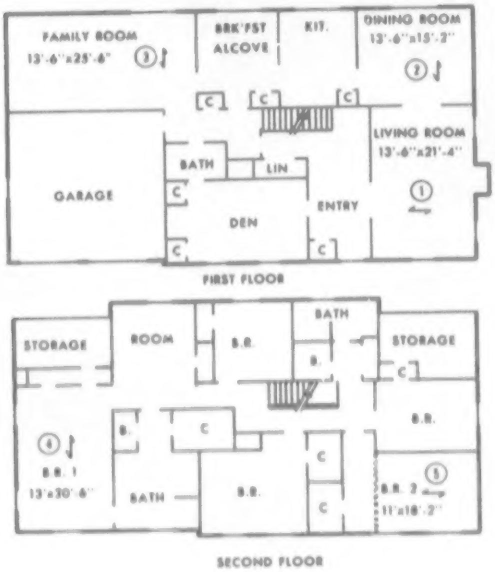


Figure 5 Horizontal Drift Under Sirulated Wind Load.

Figure 6 Floor Plan of House No. 1.


FAMILY ROOM
13'-6"x25'-6"
③
BRK'FST
ALCOVE
KIT.
DINING ROOM
13'-6"x15'-2"
②
C
C
C
LIVING ROOM
13'-6"x21'-4"
BATH
LIN
GARAGE
C
①
ENTRY
DEN
C
C
FIRST FLOOR
STORAGE
ROOM
B.R.
BATH
B.
STORAGE
C
B.R.
B.
C
④
B.R. 1
13'x20'-6"
BATH
B.R.
C
C
⑤
B.R. 2
11'x18'-2"
SECOND FLOOR

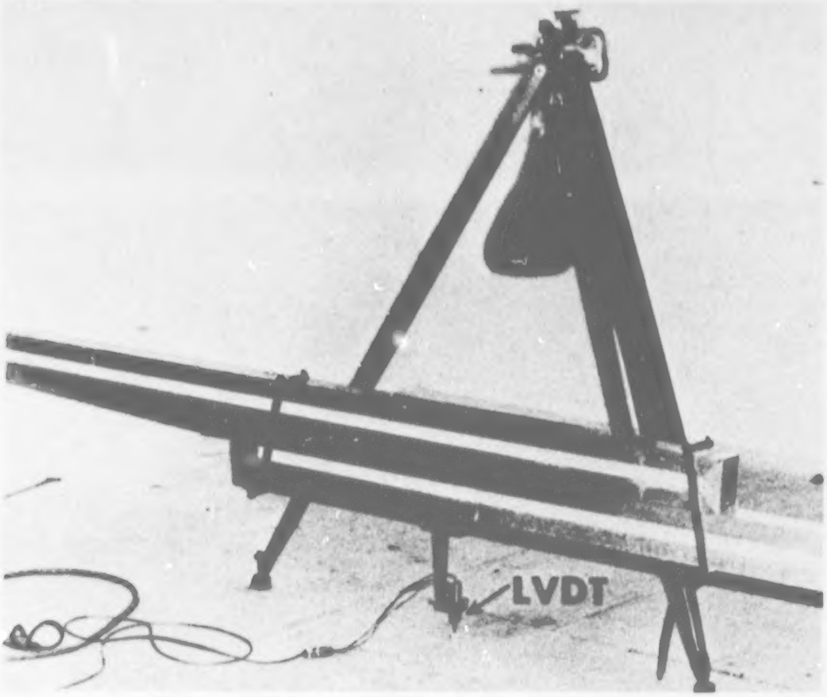
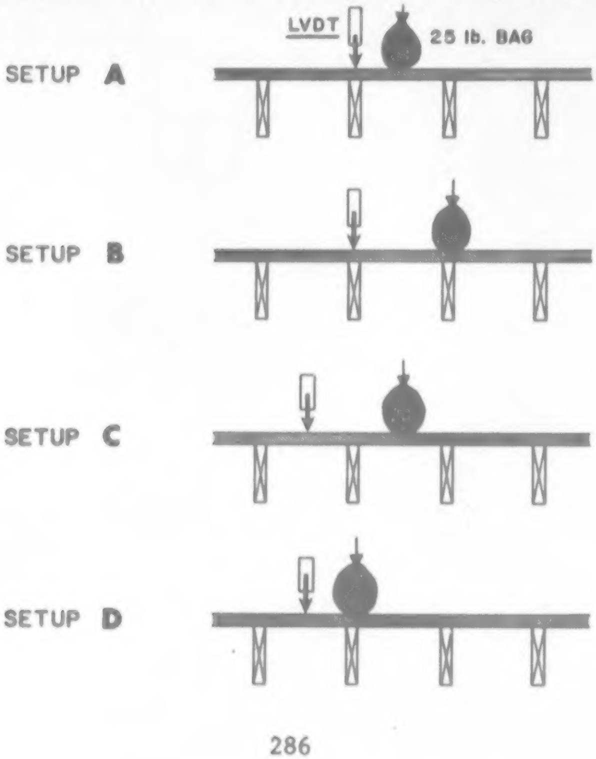


Figure 7 Photograph of Typical Test Setup.

Figure 8 Test Setup and Sequence.


LVDT
25 lb. BAG
SETUP A
SETUP B
SETUP C
SETUP D

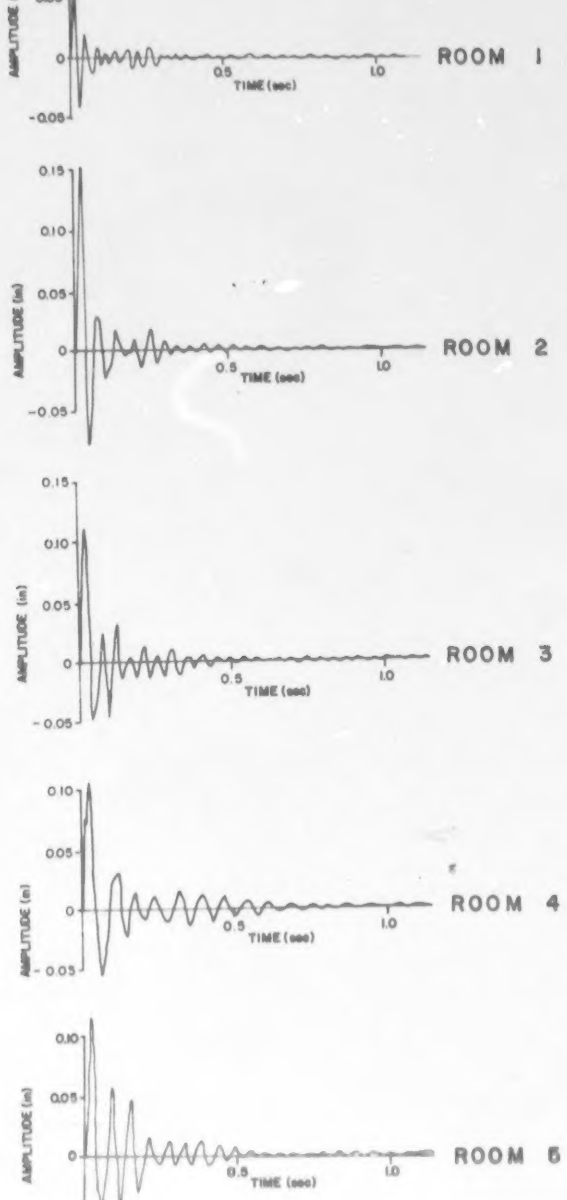
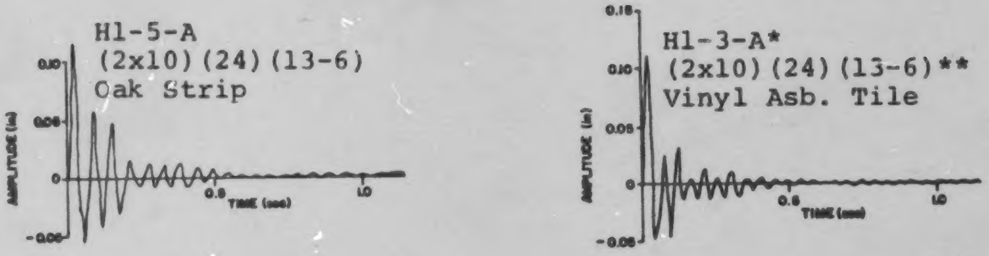
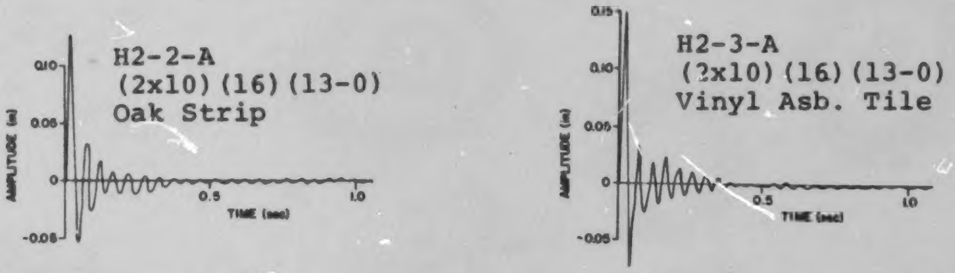


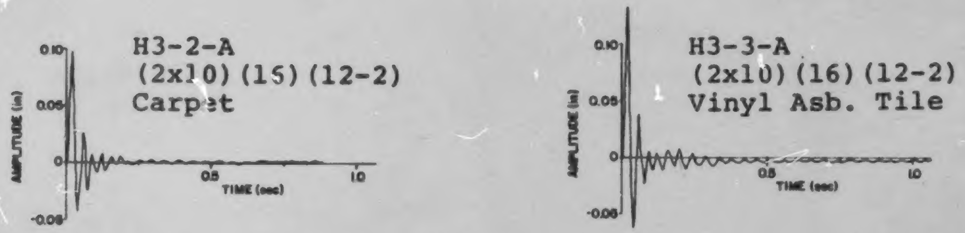
Figure 9 Deflection Traces of House No. 1, Unfurnished - Test Setup A.



(a) Oak Strip vs. Vinyl Asbestos Tile



(b) Oak Strip vs Vinyl Asbestos Tile



(c) Carpet vs. Vinyl Asbestos Tile

* House No. - Room No. - Test Setup

** (Joist Size, in) (Joist Spacing, in) (Joist Span, ft-in)

Figure 10 Comparison of Floor Responses as Affected by Floor Finish.

Pages 289-295 contained "Performance of Components: A Procedure for the Preparation of Specifications for Building Components" by H. W. Harrison, and were removed due to copyright restrictions.

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

User Requirements and Performance Design

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To establish performance goals for buildings based on extensive user requirement studies has been the basic underlying goal behind the building systems which have been developed for educational buildings in North America. Evaluating the quality of buildings has generally been a subjective question. Establishing performance criteria begins to tie quality to measurable objectives rather than more ephemeral issues. Finding those performance objectives which can be described, which are relevant to the building, which are relevant to education, and which protect the economic interests of the owning institution is neither simple nor direct. Conflicts between immediate economic advantage and long range flexibility, between comfort and economy, between low first cost and long-range operational economy make for difficult decision making.

Weighing the comparative importance of the conflicting interests of the user-client (student/teacher/dormitory resident) and the owner-client (school system/college/university) is the most subtle area of decision making and the toughest. The evaluation of whether the resulting buildings meet the performance criteria is a comparatively simple matter. Reexamining whether the performance criteria adoped was appropriate and consistent with the direction the institution has taken since the building has been built, occupied and used is a more significant and of course a more difficult question to get at.

Le but fondamental des systèmes de construction qui ont été développés pour les établissements d'enseignement en Amérique du Nord est d'établir des objectifs de performance fondés sur les nombreuses études de demandes d'usagers. L'évaluation de la qualité des bâtiments a été généralement considérée comme une question subjective. L'établissement de critères de performance amène à lier la qualité à des objectifs mesurables plutôt qu'à des conclusions plus éphémères. Il n'est ni simple ni direct de trouver des objectifs de performance qui peuvent être décrits, qui sont en rapport avec le bâtiment et avec sa jonction - l'enseignement -, et qui protègent les intérêts économiques de l'institution propriétaire. Des conflits entre l'avantage économique immédiat et la flexibilité à longue portée, entre confort et économie, entre premiers frais modérés et économie d'opération à long terme rendent la prise de décisions difficile.

L'appréciation de l'importance comparative des intérêts opposés du client-usager (étudiant, professeur, occupant d'une maison d'étudiants) et du client-propriétaire (système scolaire, collège, université) est le domaine le plus délicat et le plus difficile de la prise de décision. Décider si les bâtiments ainsi réalisés se conforment aux critères de performance est une chose relativement simple. Vérifier si les critères étaient appropriés et compatibles avec la direction que l'institution a prise depuis que le bâtiment a été construit est une question de plus grande portée et évidemment plus difficile à trancher.

Key words: ABS (Academic Building Systems); EFL (Educational Facilities Laboratories, Inc.); environmental criteria; evaluate; performance criteria; performance design; RAS (Recherches en Amenagements Scolaires); SCSD (School Construction System Development); SSP (Schoolhouse Systems Program); SEF (Study of Educational Facilities); URBS (University Residential Building System); user requirements.

Among the pioneering programs utilizing performance criteria for both buildings and building components were the various North American educational building systems programs established and financially backed by Educational Facilities Laboratories. These programs included SCSD (School Construction System Development) program in California; Toronto's SEF (Study of Educational Facilities); the RAS program in Montreal (Recherches en Amenagements Scolaires); the URBS program of the University of California (the University Residential Building System); and the Schoolhouse Systems Program (SSP) of the State Department of Education in Florida, as well as the ABS program (Academic Building Systems) of the universities of California and Indiana.

EFL, being an agency set up by the Ford Foundation to aid schools and colleges find new and better solutions to their facilities problems, was obviously more interested in the process being housed, education, than in the development of building science. Consequently the notion of trying to tie down performance in these programs in measurable terms stemmed directly from concern that traditionally conceived and built facilities weren't serving the users' needs satisfactorily. Underlying all these programs was the assumption that performance design was a new and better way to answer users' needs.

Concern with two rather different sets of user needs dominated this whole group of educational projects. The first were institutional needs, the needs of the school district or college. The second were the needs of individual users, the teachers and students who actually occupied the buildings. As school districts and university systems get larger and more bureaucratic, the institutional and user needs get further apart.

Among the major institutional performance requirements was flexibility — by which I mean here the ability to remodel — to reorganize the interior spaces — at minimum cost. Changing educational programs had been arriving on the intellectual scene with increasing frequency in the late 1950's and early 60's and these new programs were almost always in conflict with existing building layouts. Among the most frequent problems were room sizes and layouts, the availability of electrical energy for audio-visual equipment, the ability to reduce light levels (or direct glare) to facilitate the use of audio-visual devices. The cost of remodeling was usually resisted by boards of education who (with some justification) gave first priority to building new buildings or to remodeling schools no longer physically safe for human habitation.

The victim of this financial squeeze was often the new educational program, which found itself stymied by immovable walls, unchangeable structures, and audio-visual devices locked in the closet. The concept of buildings which could be reorganized with zero or minimal cost had great appeal to school administrators who wished to build schools that were not conventional in their educational planning and who needed to reassure their school boards and constituents that should the new innovative program not prove to be a success the building could be reconstituted into a conventional school building at minimal cost.

Another institutional input to establishing performance standards concerned maintenance both of surface elements (e.g. partition faces) and of operating subsystems such as heating/ventilating/airconditioning (HVAC) and lighting. The bidding requirements on public work, which in practical if not legal terms require accepting the lowest bidder on a first-cost basis alone, left a number of school districts in California anxious to do something to insure lower operating and maintenance costs.

Consequently the concept of performance design found a willing ear with institutional clients looking out for their own institutional interests.

The basic concept also found easy acceptance among those concerned with the individual users themselves. Questions of environmental conditions as well as building services can be very directly and unemotionally dealt with by using performance requirements. Probably the best — or at least the best documented — example of this is the environmental criteria developed for the SEF program in Toronto.(1) This effort to quantify qualitative requirements for atmospheric, visual, acoustic, mechanical and electric services with enough open-endedness so as not to get over-precise and rigid, proved to be a useful way to move from program requirements to building requirements (see Chart A). The genetal "Environmental Criteria" approach was loosely based on some work done earlier in the U.K. by architect Ian Moore, which he identified as the "Activity Data Method." Moore's work had been concerned with the programming of ordinance depots, but the basic format and approach to the problem was not dissimilar. (2)

Were it not for money, there wouldn't be many conflicts in taking the performance approach to design and user needs. But money is a critical issue in educational facilities. Consequently there are a series of value judgements which have to be based on an analysis of performance versus cost factors. In non-systems projects, or projects not utilizing performance criteria, these value conflicts are rarely articulated or dealt with except intuitively by the designer.

Obviously the length of structural spans is one such issue. How much is a longer span worth? In many academic areas its only value may be in the simplification of remodeling, another long-range factor prior to occupancy. In partition performance there is an extremely close correlation between the cost and sound transmission loss. Setting requirements based on acoustic quality alone is clearly not feasible economically, particularly when we don't seem to be able to get consistent data on desirable acoustic performance for instructional buildings. Furthermore the objectives of flexibility conflict directly with acoustic quality which depends largely on the weight of partitions and excellent gasketing, both of which conflict directly with ease of movement.

There was considerable criticism of SCSD for the singlemindedness of its emphasis on flexibility, but discussions with the occupants of the original SCSD schools and discussions with educators regarding the later systems schools based on the same performance requirements would suggest more rather than less flexibility. In review, flexibility factor difficulties often cited by administrators include:

1. Too many services located in the partitions, which
   a. Cost a lot to move, and
   b. Damage the partition panels when they penetrate them;

2. The difficulty and/or expense of moving the partitions themselves, and

3. The cost of redoing flooring after partitions have been moved, particularly carpeting, when the carpeting was not laid under the partitions originally.

Ease and economy of spacial reorganization seems in many cases to be less than it should have been from the occupants' standpoint. Subsequent projects, including a number we have done at Caudill Rowlett Scott, have tended to choose the partitions introduced since the original SCSD program and which make some acoustic sacrifice in favor of ease of movement.

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1 and 2 Figures in parentheses indicate the literature references at the end of this paper.

First-cost versus maintenance cost is another conflict area, one normally encountered in building design. It is usually settled pragmatically in favor of low first-cost. For example, the school districts which made up the original SCSD project were all concerned about the high operating and maintenance cost of airconditioning systems, which they had acquired through traditional bidding procedures. The SCSD airconditioning system was bid with a maintenance contract for five years (an optional extra), renewable for three more such five-year periods at the sole discretion of the school district. This was, of course, an effort to build a quality response into the bidding process and to avoid shoddy, low first-cost products. However in the final analysis only one of the school districts exercised the privilege of accepting the maintenance contract as part of the original bidding, the rest preferring lower first-cost.

Among the other conflicts which can only be solved by value judgements are the conflicts of the user client, i.e. the student or teacher or dormitory resident, and the owner client, i.e. the educational institution. An example of this is the ability to move partitions around in college housing. This quality doesn't directly serve the user, but it does protect the institution from building buildings which can't be adapted to the current life style of their prospective student-tenants. Thus this flexibility protects the institution, but makes little difference to the student during his year of occupancy. On the other hand, the ability to paint the walls a color of which he approves is a value to the student but, at least in the case of the University of California, was a detriment to the institutional interests, which were concerned lest the students paint their walls in colors that were in bad taste. Consequently technology had to develop a wall covering technique, a series of nylon clips, which would enable the student's wall covering to be changed at will and removed at year end. A triumph of technology over bureaucracy.

There have been a number of efforts to evaluate some of the educational building systems programs, but none really basic enough. It's been easy enough to find out whether or not a partition actually performs acoustically as well as it's supposed to. It's somewhat more complicated but possible to find out whether an airconditioning system or a ceiling/lighting system performs in accordance with the performance specifications under which it was bid. But to find out whether the issues which led to performance criteria were the correct issues on which to focus is a far more subtle question. How important are these environment elements like airconditioning, lighting quality, acoustics, fire protection, flexibility, electrical distribution, and so on,when compared to such traditional architectural elements as commodity, firmness, and delight.

The lack of time and the lack of serious effort to evaluate the existing buildings which have resulted from performance design make it difficult to evaluate its effectiveness in isolating the critical and relevant elements in building. Performance specifications are no substitute for design, but they do offer a thoughtful alternative to intuition in specifying the products which make up our buildings. If the use of performance specifications avoids becoming a new, rigid, and Jesuitical faith, the concept will be an increasingly important design tool.

(1) See SEF, E-1, E-2 and E-3 Educational Specifications and User Requirements for Elementary, Intermediate and High Schools. The Ryerson Press, Toronto, Canada 1969 and 1970.

(2) Activity Data Method, Ministry of Public Buildings and Works, London, Her Majesty's Stationery Office, 1966, and Planning a Major Building Programme: same source; 1966.

Level K-6	Square Feet 750	Area Teaching Station	Page Number 97

Environmental Criteria

Atmospheric Criteria

Temperature	outside temperature > 90 F°	78°	± 2°
	< 0 F°	72°	± 2°
Relative Humidity	outside temperature > 90 F°	50%	± 5%
	< 0 F°	30%	± 5%
Outside Air	CFM per sq ft	0.3 to 0.8	> 0.2
	CFM per person	15 to 30	> 8
Air Changes	per hour	6 to 8	> 5
Air Movement	velocity: FPM	25 to 40	± 10
Room Pressure	in. WG	+ 0.10	> + 0.05
Air Filter Efficiency	> 5μ	80%	> 85%
	< 4μ	45% to 80%	—
Odors Body			
Population	max 36	min 0	
Heat Gain	source	watts	BTUH
	Lighting	3 to 4/sq ft	
	AV equipment	—	
	Projector	—	

Double glazing

Visual Criteria

Visual Performance Index (VPI) 63.0			Ft Candles N/A
View Out Op'l	View In Op'l	Blackout Yes	Privacy No
Daylight Op'l	Level Control Yes		

Acoustic Criteria

Ambient Noise Level: NC 35 max

Reverberation Time (in seconds)	Frequency: cps	125	250	500	1000	2000
	max			1.0		
	min			0.5		
Generated Noise Level (in db re .0002 dynes/cm²)	Frequency: cps	31.5	125	500	2000	8000
	design level			77		

Impact noise is a considerable problem.
Acoustic treatment of the floor is recommended.

Services

Mechanical Services

CW No	HW No	Steam No	Gas No
Air No	Drain No	Exhaust No	
Other			

Electrical Services

PA Yes	Intercom Yes	Handset Yes	Bell Tel No
Program System Yes		Clock System Yes	TV Terminal Yes
Computer Terminal Yes		Underfloor Duct System No	
Power 110V–1 ϕ for AV equipment			
Other Consider induction loop system			

Notes

CHART A Example of SEF Environmental Criteria

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

Paths to Performance - Some Recent Projects Employing the Performance Concept

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Two building research and development programs, organized and directed by our firm (BSD)[1], have utilized the performance concept, each with a different approach and end result. Both projects were based on earlier experience coordinating the School Construction Systems Development (SCSD) program.

Based on an analysis of user requirements, performance specifications and/or requirements were developed on the URBS (University Residential Building System) program for University of California student housing, and on the ABS (Academic Building Systems) program for Indiana University and University of California academic buildings.

The URBS project involved performance specifications to guide the development by manufacturers of five new subsystems for student housing. Specifications for the subsystems were written to accommodate cooperation between bidders and to assure an integrated design proposal. Product development to meet the URBS performance specifications was based upon a large, guaranteed market. The ABS program on the other hand, could not guarantee a future market and therefore assumed the selection of existing, already developed, products for its five subsystems.

Based on the experience gained from the URBS and ABS projects, the paper calls for the encouragement of public agencies to collect and develop, as necessary:

- methods expressing man's environmental needs in performance terms;
- scales for displaying various levels of performance;
- methods for relating levels of performance to various activities or spaces as they occur in buildings; and
- models for using performance-oriented requirements in building and building systems procurement processes.

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[1] The meaning of abreviations are listed at the end of the paper.

Deux programmes de recherche et de développement dans la construction, organisés et dirigés par notre compagnie, ont utilisé le concept de performance, avec une approche et un résultat final différents pour chacun. Les deux projets étaient fondés sur une expérience préalable coordonnant le programme du SCSD (Développement de systèmes de construction d'écoles).

Fondées sur une analyse des besoins des usagers les spécifications et/ou exigences de performance furent développées dans le cas du programme de logements d'étudiants de l'Université de Californie (URBS) (Système de construction de residences à l'Université) et dans celui du programme ABS (Système de construction de bâtiments académiques) de l'Université d'Indiana et des bâtiments académiques de l'Université de Californie.

Le Projet URBS impliquait des spécifications de performance pour guider l'exécution par des entrepreneurs de 5 nouveaux sous-systèmes pour le logement des étudiants. Les spécifications pour les sous-systèmes furent établies pour assurer la coopération entre adjudicataires et pour garantir un projet intégré. Le développement du produit pour se conformer aux spécifications de performance URBS pouvait compter sur un large marché garanti. Le programme ABS ne pouvait pas garantir un marché futur et par conséquant a assumé la sélection de produits existants pour ses 5 sous-systèmes.

D'après l'expérience acquise avec les projets URBS et ABS, cette communication demande aux agences publiques de collecter et de développer comme nécessaires:

- des méthodes exprimant les exigences d'environnement de l'homme en termes de performance;

- des barèmes pour exposer les divers niveaux de performance;

- des méthodes pour établir des rapports entre degrés de performance et les activités ou espaces divers à mesure qu'ils se présentent dans les bâtiments; et

- des modèles pour la mise en pratique dans la construction d'exigences orientées vers la performance et les moyens d'obtenir des systèmes de construction.

Key words: ABS; building systems; college buildings; dormitories; HVC; laboratories; lighting/ceiling; performance specifications; procurement process; SCSD; structure; subsystem; URBS.

1. Introduction

The intent of this paper is to describe, analyze and compare two building systems research and development projects which used the "performance" concept as a means of expressing certain kinds of requirements pertaining to building components.

There are a number of different ways of interpreting what "performance" is and how the concept is useful to the building design and construction process. The following definition, therefore, of what is meant by "performance" relative to the projects which will be described in this paper,is presented. Performance requirements are defined as a subset of a larger set of requirements for building which are "non-prescriptive" in nature. This larger set is composed of statements of need which do not suggest or preconceive a particular technological solution but, rather, are generalized and objective in nature. Performance requirements are non-prescriptive, objective statements which describe a level of expectation relative to behavior of physical building elements. They may be quantitative or qualitative in nature. Non-performance, non-prescriptive requirements include cost criteria, spatial and functional needs, etc. which refer to the non-physical building parts or to the building as a whole.

Before presenting descriptions of practical applications of performance requirements, a brief discussion of the rationale behind,and derivation of,performance requirements is also presented in order to clarify the approaches to the projects described later.

The reasons for using performance or non-prescriptive requirements statements in developing criteria for design and procurement include the following:

-Performance requirements encourage and improve the climate for technological advance. Statements of requirements for built environment in abstract non-prescriptive terms do not limit the range of technical solutions which may be developed for a given project. In other words, a statement that a room should be separated by a barrier which provides an STC rating of not less than 40 enables many more technical solutions to be developed and considered than does a statement that rooms should be separated by a partition constructed of 2' x 4' wood studs, 16" on center and faced with 5/8" gypsumboard on either side.

-Performance-oriented statements enable different technological solutions to a given set of requirements to be bid against one another. For example, if performance-oriented requirements are established for a structural system defining only such aspects of structural behavior as deflection and load-carrying capacity, structural frames may be bid against bearing wall structures, and/or against space frames. If, however, requirements were established which pre-selected a concrete bearing wall structure as the generic solution, then one could only receive bids from different producers of that particular structural solution. The result, in this case, would not be a selection of the cheapest structure; or, for that matter, even the cheapest bearing wall structure.

Performance (or non-prescriptive) requirements for buildings are derived primarily from analyses of the needs of the users of the buildings, i.e., tenants, operators and owners. The evolution of performance requirements from user needs analyses has often been described as developing quantitative expressions of requirements from qualitative expressions. Such a distinction is perhaps valid in an idealistic context; however, in practice, non-quantitative, non-prescriptive statements often remain useful in connection with performance requirements.

2. Experience with Performance Requirements

Over the past several years, our office (Building Systems Development, Inc.) has been using the performance concept as described above as part of a series of research and development programs. The first project which utilized performance requirements was the much-publicized School Construction Systems Development (SCSD) project, which was begun in 1961. Subsequently, two other projects which utilized performance requirements were initiated and completed: the University Residential Building System (URBS) project and the Academic Building System (ABS) project. The manner in which these latter projects utilized performance requirements will be the focus of the remainder of this paper. A brief description of the SCSD project will also be presented in order to provide a historical framework for the reader.

The SCSD project was organized and managed by a group of men including Ezra Ehrenkrantz and Christopher Arnold, who were later to found Building Systems Development, Inc. (BSD) in San Francisco, California. The objective of the SCSD project, not surprisingly, was to develop a building system; that is, a set of standardized components designed to be assembled in a variety of configurations to meet the varying site and program requirements of a number of clients. The clients in this case were thirteen school districts. It was felt at the outset of the program, and later proven correct, that the building systems approach would provide considerably higher quality educational environments at no increase in cost. Investigation of the needs and requirements of the school districts and the performance capability of building components on the market indicated that new technological solutions were needed if client requirements were to be met. In order to facilitate and direct the development of new school building technologies, the purchasing power of the thirteen school districts was organized and aggregated, performance requirements were established for five categories of building elements found in school construction, and building manufacturers were asked to develop new product solutions to those requirements. The five categories of components were structure, HVC, Lighting/Ceiling, partitions and cabinets. Non-prescriptive performance requirements allowed each manufacturer to develop technological solutions which not only met the requirements of the buyer but which also corresponded to his own experience, production expertise, and marketing capability. The bid solutions submitted in each component category covered a wide range of different materials and technologies. The costs of these solutions were capable of being compared, due to the adherence to common sets of non-prescriptive performance standards.

3. Two Recent Projects Using Performance Requirements

The approach to performance-oriented procurement used on the SCSD project provided a point of departure for both the URBS and ABS projects. The URBS project followed generally the development process established in the SCSD project. An aggregated and guaranteed building market was offered by the University, and new components were designed and developed by industry for that market in response to performance specifications.

The universities which were sponsoring the development of ABS, however, were not able to guarantee a large predictable market of academic facilities over a period of time, so a different development approach was needed. In this case, a building system was designed inhouse by BSD in response to previously determined performance requirements and utilizing on the market, existing components.

In brief, the nature of the market and the degree of technological innovation involved were the two essential areas of distinction between URBS and ABS. A comparative summary of the two projects is presented below.

URBS	ABS
Client: The University of California.	Client: The University of California along with Indiana University.
Building type: Dormitories from one to thirteen stories.	Building type: Science and engineering buildings, including laboratory, shop, classroom and office spaces.
Market: A market of 2,000 dwelling units over 3 years guaranteed by the University.	Market: Unlike URBS, no market for ABS facilities could be guaranteed by the two institutions.
Development approach: Procurement of a building system design consisting of new technological solutions to building components by manufacturers' response to performance specifications.	Development approach: Unlike URBS, development of a building system by coordinating and utilizing existing, on-the-market technology.

Objectives:

- to provide an environment in which the student can express his individuality.
- to improve physical comfort and privacy within the student room.
- to do away with standardization of appearance in student rooms and buildings.
- to eliminate physical environment deficiencies: poor acoustics, inadequate ventilation, and restrictions on room decoration.
- to reduce the costs of ownership: construction, operation and maintenance.
- to increase the space adaptability so that it can be reorganized in response to student preferences, as well as changing administrative policies.

Objectives:

- to improve the performance of buildings and building subsystems in response to specified requirements.
- to provide equal performance for lower cost or better performance for the same or lower cost, when compared with conventional construction.
- to accommodate major changes in space utilization quickly and economically.
- to facilitate application of improved planning methods for the simplification of schematic design and the refinement of cost control.
- to reduce design and construction time through more efficient procedures.

Components categories:

Structure/Ceiling
Heating/Ventilating/Cooling
Partitions
Bathrooms
Furnishings

Components categories:

Structure
Heating/Ventilating/Cooling
Partitions
Lighting/Ceiling
Services Distribution

Both the URBS and ABS projects used performance-oriented statements of requirements to guide the development of their respective technical solutions. Excerpts from the performance statements used for each project are presented below. It should be kept in mind, however, that the performance statements used in URBS were part of a set of specifications used as contract documents to procure compatible building subsystems designed by manufacturers, while performance statements used in the ABS project served only as in-house guides to the design by BSD of the actual building system.

3.1. Example Structure Performance Statements

(a) URBS

Fire Rating: Low-rise structures shall meet the requirements for Type IV one-hour construction in the UBC 1967 Edition as a minimum requirement. High-rise structures shall meet the requirements for Type I construction in the UBC 1967 Edition. These buildings will be 5 to 13 stories.

Vertical Loads: Roof loading - Live load: 20 lb./sq.ft. Code reductions may be applied in accordance with UBC 1967 Edition. Dead load: allow 10 lb./sq.ft. for roofing, insulation and miscellaneous, in addition to dead load of structure/ceiling.

Floor loading - Live load: 50 lb./sq.ft. Code reductions may be applied in accordance with UBC 1967 Edition. Dead load: assume 20 lb./sq.ft. for partitions and 6 lb./sq.ft. for non-URBS items. In addition to dead load of structure/ceiling, also allow for HVC component category equipment.

(b) ABS

Fire Rating: The structural system shall conform to the requirements for Type I (UBC) or Type A (NBC) construction to provide the following fire ratings: slabs, beams, girders - 3 hr.; columns - 4 hr.; and grid frame - 4 hr.

Vertical Loads: All structural components shall be designed to support the following superimposed loads. Uniform live loads: roof - 40 psf; floor - 70 psf; and ceiling - 20 psf. Concentrated live loads: Floors shall be designed for a concentrated load of 2,000 pounds placed upon any space 2'6" square. Uniform dead loads: The following minimum dead load values, applicable for high normal weight aggregate concrete only, shall be assumed, which include structural weight, partition allowance, and weight of HVC and service equipment. Roof - 91 psf; floor - 102 psf; and ceiling - 10 psf.

3.2. Example Heating/Ventilating/Cooling Performance Statements

(a) URBS

Heating/Cooling: Design temperature - The indoor dry bulb air temperature shall be maintained between 73° and 77°F. within the occupied zone whenever the MRT is approximately equal to that temperature.

When the MRT in an occupied zone differs from the air temperature, the design temperature shall be reduced 1.4°F. for each 1.0°F. MRT elevation above the air temperature, and vice-versa.

If the overall variation in the air temperature cycle is 2°F. or more at any point in an occupied zone, the rate of change of temperature shall not exceed 4°F. per hour.

If the overall variation in the MRT cycle is 1.5°F. or more at any point in an occupied zone, the rate of change of MRT shall not exceed 3°F. per hour.

Ventilation: Fresh air introduction - As required for odor dilution: 20 CFM per person. Assume the following occupant loads. Spaces: FLA (incl. bathroom and internal circulation), public corridor, lobby and stairway - 100 sq.ft./person, 0.2 CFM/sq.ft.; Library, hobby room, darkroom, laundry, office, lounge not in FLA - 50 sq.ft./person, 0.4 CFM/sq.ft.; classroom, music practice room, conference room, seminar room, study room and typing room not in an FLA - 20 sq.ft./person, 1.0 CFM/sq.ft.; and recreation room, TV and hi-fi rooms - 10 sq.ft./person, 2.0 CFM/sq.ft.

Air motion within occupied zone - 10 fpm minimum, 35 fpm maximum when cooling, and 45 fpm maximum when heating, in any direction.

Filtering - Filter all air supplied mechanically to occupied spaces. Filters shall be not less than 45% efficient when tested in accordance with the National Bureau of Standards Dust Spot Test Method (atmospheric). Filtering for room air tempering supply air at the terminal shall meet industry standards.

(b) ABS

Heating/Cooling: Room temperature - The subsystem shall have the ability to maintain 73°F. on a summer design day and 73°F. on a winter design day. Each control zone shall be locally and independently adjustable to maintain the set temperature plus or minus one and one-half degrees ($\pm 1\text{-}1/2^{\circ}$).

Room relative humidity - The subsystem shall have the ability to maintain relative humidity within the range of 30% to 60% at a 73°F. room temperature, when room sensible heat ratios are in the range of 90% to 100%.

Ventilation: Room air quantities - The minimum total air circulation rates shall be as follows. Offices - 1 CFM/sq.ft., 6.7 air changes/hr.; classrooms - 1-1/2 CFM/sq.ft., 10.0 air changes/hr.; laboratories - 2 CFM/sq.ft., 13.3 air changes/hr.; corridors - 1/2 CFM/sq.ft., 3.3 air changes/hr.; and toilets and janitor closets - 2 CFM/sq.ft.

The maximum air circulation rate shall not exceed 3 CFM per square foot.

Outside air ventilation - The design shall include the following minimum outside air quantities. Offices - 25 CFM per person; classrooms - 15 CFM per person; laboratories - 20 CFM per person; corridors - 1/4 CFM per square foot; and lobbies - 1/4 CFM per square foot.

If the function of an area of the building is undetermined, use 1/2 CFM of outside air per square foot.

An additional requirement is that the system shall have sufficient outside air to make up for 100% exhaust laboratory rooms, fume hood and special exhaust systems, and result in building pressurization.

Room air velocity - Air motion within the occupied zone, between 3" and 72" above the floor, shall be between 20' and 50' per minute.

3.3. Example Partition Performance Statements

(a) URBS and ABS

Fire Requirements: All partitions shall be non-combustible. The smooth finish and textured finish panels shall have a maximum flame spread not greater than 25. All others shall have a flame spread rating not greater than 225.

The ASTM E84 Tunnel Test shall be used for all flame spread determinations. The ASTM E119-61 test procedure shall be used for determining all fire-resistive construction standards.

Acoustical Requirements: Acoustical test procedures shall follow ASTM E90-61T "Laboratory Measurement of Airborne Sound Transmission Loss of Building Floors and Walls" except that large panels (9' x 14') shall be used and not the small panels (1'6" x 6'6") permissible under E90-61T. Acoustical tests shall be performed under field conditions.

All solid panel types shall provide an STC rating of not less than 40.

All panel types containing glass shall provide an STC rating of not less than 20.

Provide doors having an STC rating of not less than 27. Raised thresholds with a maximum height of 3/4" above site floor will be permitted. Bidders shall submit drop seal and sweep seal designs for specific approval if they wish to have such seals considered.

Glass doors shall provide an STC rating of not less than 20.

Impact Strength Requirements: Perform impact load tests in accordance with ASTM E72-61, Section 12 of 13. Conduct tests on doors and partition panels 8' in height with the largest stud spacing provided. Impact shall be midway between studs. For five drops of 2', panel shall not fracture, and the temporary deflection shall not exceed 1". The permanent set shall not exceed 1/16".

Perform this test with standard connections to URBS structure/ceiling and carpeted concrete floor. Door closers and checks shall not be used in this test.

Each panel type except glass, tackboard and chalkboard shall withstand the impact of an 8-oz. 1-1/2" diameter steel ball dropped 18" without cracking or chipping.

Surface Durability Requirements: Abrasion: Textured panel - Use Wyzenbach method under Federal Specification CCC-T-191B, Method 5304. There shall be no exposure of base or backing material after 300 double rubs.

Smooth panel and doors - After 150 cycles on Gardner Model 105 Washability and Abrasion machine, using cheesecloth over felt pad, the change in gloss shall not be greater than ± 5% as measured by Gardner 60° glossmeter.

Humidity resistance - 100 hours in atmosphere with 100% humidity and temperature of 70° - 75°F. with no appreciable deterioration.

Washability - 100,000 brush strokes while continuously wetted by a 5% solution of trisodium phosphate in a Gardner 105 Straight Line Washability Machine without any softening, color change or more than slight abrading of the surface. Perform this test over the joint of laminated surface materials.

Ultra-violet resistance - There shall not be appreciable color change after 150 hours at approximately 150°F. in the Atlas Fadeometer.

(b) ABS

Demountability: For the two panel types, one-hour fire-rated and non-fire-rated, the following shall apply as minimum standards of demountability.

A single panel in the center of a 12' run shall be capable of being removed and replaced in one hour by two men.

100 linear feet of partition shall be capable of being removed, moved and re-erected nearby in 80 man-hours, or 40 hours by two men. This moving process shall be accomplished with minimum soiling of the building.

The weight of no element of this partition system shall exceed 200 pounds.

3.4. The Systems Developed

Based on a complete set of performance statements including the examples presented above, building systems were developed for both the URBS and the ABS projects. Brief descriptions of each of the systems developed are presented below with drawings illustrating each system presented at the end of this paper.

(a) URBS System Description

Spatial Concept: A flexible living area (FLA) consisting of a one-hour fire-protected envelope defined by floor, partitions and ceiling; up to 2,000 sq.ft. in area; and designed for 10 students maximum.

Structure/Ceiling Subsystem: A combination precast and cast-in-place concrete structural frame was developed. Included was all structural work above the ground floor level: columns, beams, floors, finished ceilings, roofs, access panels, balconies, stairs and shear walls. Also included was an electrical raceway attached to the ceiling through which electrical wiring was run to the partitions. All structural elements were fire-resistive, of reinforced concrete, with domed voids occurring in 18"-deep, hollow floor slabs. These voids accommodated supply air ducts, plumbing and electrical services, while also serving as a plenum for air return. Spans ranged from 13'4" to 45'0".

Heating/Ventilating/Cooling Subsystem: All mechanical equipment required for heating and ventilating with cooling optional was provided. Areas up to 2,000 sq.ft., subdivided as desired into various living arrangements, were serviced by multi-zone units. The ventilation capability permitted up to 100% outside air. Chilled water and hot water were supplied from a central campus plant, or by the URBS factory-packaged mechanical unit. Component elements provided for bathroom heaters, air distribution, kitchen hood and room exhaust.

Partitions Subsystem: Fixed or demountable one-hour fire-rated partitions with a wide selection of surface colors, textures and materials were provided. Fixed partitions were 8, 10, 12 or 14 feet high; demountable partitions were 8 or 10 feet high. Opposite faces of partitions could be removed and replaced independently. The component design provided for concealed electrical services, and included picture hanging devices and vertical supports for shelving, counters and cabinets.

(b) ABS System Description

Spatial Concept: A space module which was a one-story block of building volume, dimensionally coordinated with the integrated subsystems. The space module had an area of 10,000 sq.ft. ±25% with a variable but limited aspect ratio. This resulted in a total of about 40 different space module alternatives, each of which could be internally organized in various ways to accommodate a range of functions.

Structure Subsystem: A girder, beam, slab system was designed which could be constructed from cast-in-place concrete, precast concrete, fire-protected steel. Bay sizes were 20' x 20' to 30' x 40' in 10' increments. Lateral forces were taken by a perimeter grid frame. Floor-to-floor heights were either 16'10" or 14'7".

Heating/Ventilating/Cooling Subsystem: All three services were provided for a mechanical service module of 10,000 sq.ft., ±25%, by a single-duct reheat system. One fan room was included in each space module. Either a building boiler room or campus central plant could be used. A plenum return was used with ducted special exhaust. Up to 30 temperature control zones were provided at each floor with a roof exhaust.

Partition Subsystem: All partitions were demountable, and of one height. No partitions penetrated the ceiling. Gypsum facings with high quality paint or vinyl finish were used. A 5' x 5' planning module was used; off module locations were permitted where required. Lab utilities were outside partitions; switch legs, control wiring, isolated electrical outlets were within the partition.

Lighting/Ceiling Subsystem: A suspended-ceiling was designed with integral lighting fixtures, providing a uniform ceiling height for each space module, of nominally 9'0". Two types of access to service space were developed: an access ceiling and a catwalk ceiling. A 5' x 5' module was used in the design.

Utilities Distribution Subsystem: All verticals were concentrated in one mechanical tower per space module. All horizontals were zoned in service space above each floor. Two types of access were provided: horizontal by catwalks and vertical through access ceiling.

4. Problems Encountered with Performance

Two kinds of problems are encountered in trying to set performance requirements. The first set of problems relate to trying to match proposed performance standards to both the needs and the resources of the user. Thus the writer of performance requirements must be aware of the cost implications of the standards he is demanding from industry, and he may have to temper the user's expectations. This problem is particularly acute in a systems development program such as URBS, where expectations tend to be higher, and costs more conjectural. As an example, the high acoustical standards of the HVAC system that were demanded resulted in a fairly high cost system. In one case, a potentially strong bidder decided, after many months of research and development, that the risks were so great of not being able to meet the standard that he did not submit a bid.

The second group of problems relate to defining the performance standards themselves. This is still a fairly new act, and information is incomplete. More work is necessary in relating performance standards to user need. And more knowledge is necessary in the definition of standards and, in particular, of test procedures. In the URBS program, much difficulty was experienced because of the inability of the variety of acoustic consultants involved to reach agreement on appropriate definition of standards and test procedures. In addition, the relevance of the acoustic standards, to the user's needs and resources, remains in question.

5. Summary and Conclusions

Performance requirements were used in two different approaches to building system procurement in the projects described above. As mentioned earlier, such requirements were used in URBS to guide the development of new products, while, in ABS, performance criteria were used as guidelines for the selection of existing, already-developed products. A generalized approach to building system procurement which results from combining the approaches used in URBS and ABS is shown at the end of this paper (Fig. 1).

While the projects which will be described in this paper resulted in building systems[1], performance requirements may be used in the procurement of more conventional construction as well. The use of performance requirements, therefore, need not necessarily be linked only to building systems. In general, performance, or non-prescriptive requirements, may be used in place of conventional prescriptive specifications if accompanied by non-prescriptive drawings which substitute for conventional working drawings. Drawings which indicate modules, interface conditions, general building configuration, proportions, etc., of building elements are all that is necessary or desirable when performance requirements are used. With performance requirements specifying quality only, and not material or technology, such non-prescriptive documents may be used to generate bidding between a variety of technical solutions in a variety of materials, thus increasing the potential of obtaining the lowest possible cost for the desired quality.

The development of the use of performance requirements from the SCSD project to the URBS project to finally the ABS project has demonstrated that performance requirements may be used quite effectively to procure existing, on-the-market building components, and are not restricted solely to the procurement of new technology, as has often been misunderstood.

It is evident from the experience gained in the projects described above that performance-oriented expressions of building requirements already exist in many diverse forms such as model building codes, material standards, etc. It is also evident, however, that in order to use performance requirements comprehensively on a building project, statements of performance have to be developed anew for many aspects of building.

As a more general observation in light of the URBS and ABS experience, it has been seen that man's requirements for environmental quality do not change nearly as rapidly as does the technology for accommodating those requirements. It would be useful, therefore, to develop and organize information which expresses those requirements in non-prescriptive performance terms at a regional or national level so that, each time a building project is attempted, time will not have to be spent developing performance statements for various aspects of the project.

This paper, therefore, calls for the encouragement of public agencies to collect and develop, as necessary:

- methods expressing man's environmental needs in performance terms;
- scales for displaying various levels of performance;
- methods for relating levels of performance to various activities or spaces as they occur in buildings; and
- models for using performance-oriented requirements in building and building systems procurement processes.

Such a collection of performance data should be classified according to at least two aspects: space types (or activities) and building components. Such a format for information display would be useful for organization of other non-prescriptive requirements, e.g., building costs, as well. An example of such a format for academic building requirements is diagrammed in figure 2 at the end of this paper.

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[1] For the purposes of this paper, building systems differ from conventional buildings in that they are inter-related building parts with the capability of being assembled into a wide variety of building forms, while conventional buildings are building parts which have the capability of being assembled into only one configuration, i.e., the building for which they were designed.

Performance requirements are only one form of recorded information pertaining to building design and construction and, as such, are conducive to all forms of information processing. Responsible development and organization of non-prescriptive performance requirement data could establish a basis for evaluating and guiding the accelerating rate of technological innovation in building while providing virtually none of the constraints to change which earlier approaches to defining building requirements have represented.

Abreviations

BSD	Building Systems Development, Inc.	NBC	National Building Code
SCSD	School Construction Systems Development	psf	Pounds per square foot
URBS	University Residential Building System	MRT	Mean Room temperature
ABS	Academic Building Systems	FLA	Flexible living area
STC	Sound Transmission Coefficient	CFM	Cubic feet per minute
HVC	Heating, Ventilating, Cooling	fpm	Feet per minute
UBC	Uniform Building Code	HVAC	Heating, ventilating, air conditioning

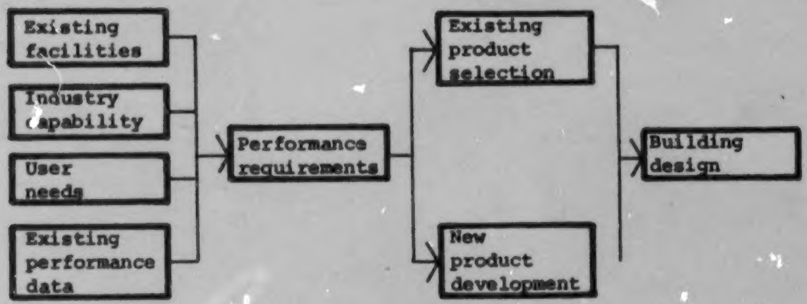
Existing facilities
Industry capability
User needs
Existing performance data
Performance requirements
Existing product selection
New product development
Building design

Fig. 1 Generalized approach to building system procurement.

Subsystems	Space Types: Offices	Classrooms	Laboratories	Corridors	Lobbies	Toilets
Structure						
HVAC						
Partitions						
Lighting/Ceiling						
Utilities Dist.						

Fig. 2 Performance data display format for academic buildings.

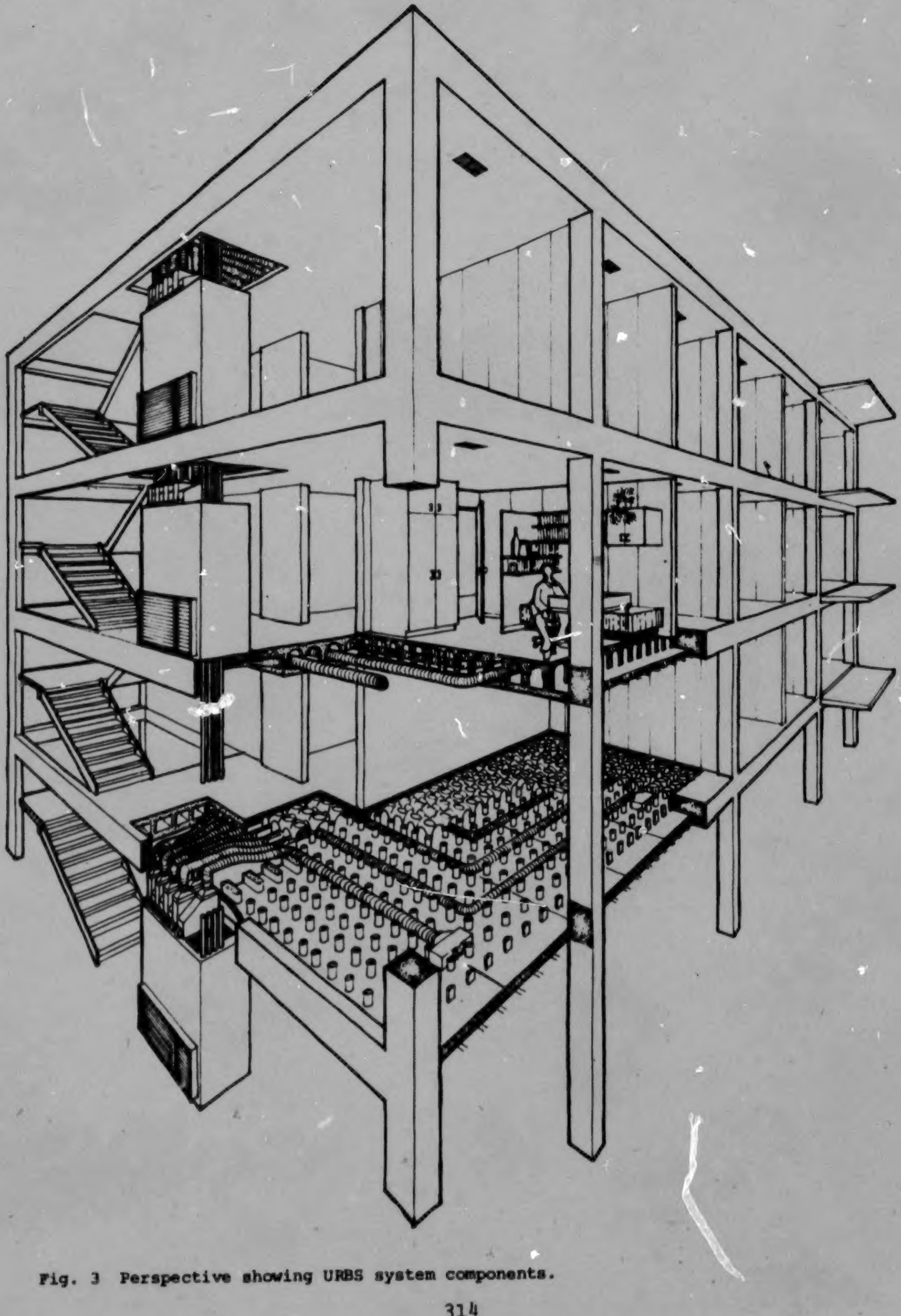

Fig. 3 Perspective showing URBS system components.

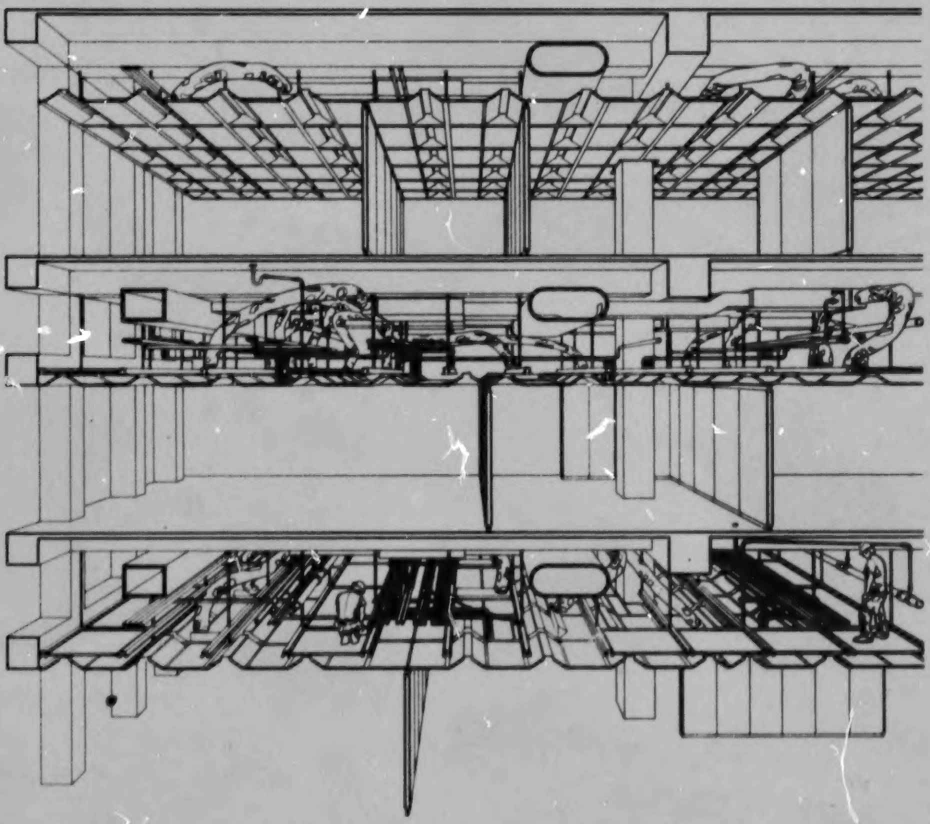

Fig. 4 Perspective showing the ABS system components.

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

The "Recherches en Aménagements Scolaires" (R.A.S.) Project
- A case study -
Strategy implemented for the development of a building system for educational facilities through the Performance Concept.

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The R.A.S. Project (Research in School Facilities) [1][1], was conducted by the author for the Montreal Catholic School Commission. Both the recognition of a basic problem common to all school districts, and the acceptance of a problem solving direction experimented with in California through the S.C.S.D. Project[2], are at the origin of the R.A.S. Project. The problem is the inadequacy of traditionally accepted methods to provide educators with appropriate and adaptable facilities within limited financial boundaries and the direction is the adoption of the "Systems Approach" for viewing and solving the problem, and the "Performance Concept" as a means for achieving the objectives subsequently defined.

The Performance Concept approach was instrumental in harnessing Canada's industrial resources and potential for the development of a building system (presently under implementation) integrating the following sub-systems:

(1) Structural
(2) Heating-Ventilation-Cooling
(3) Ceiling-Lighting
(4) Internal Space Subdivision
(5) Electric-Electronic Distribution

The strategy enforced and the means implemented through the various stages of the project, as well as the subsequent results are discussed throughout.

The paper covers:

- the project's specific context,
- the main surveys conducted to establish a basis for Performance Specifications, from user requirements to evaluation of resources,
- the major Performance Requirements developed to identify the problems for which a solution was sought,
- the Performance Criteria defined to qualify and quantify the required levels of performance,
- the evaluative methods implemented during the pre-bid, bidding and development phases of the project (scientific measurement, empirical evaluation and economic evaluation) to test and evaluate the building systems "as a whole" and at the level of their individual sub-systems.

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[1] Figures in brackets indicate the literature references at end of this paper.

Le Projet "Recherches en Aménagements Scolaires" (R.A.S.) a été dirigé par l'auteur pour la Commission des Ecoles Catholiques de Montreal. L'initiative de ce projet a été provoquée par les remarquables résultats obtenus en Californie dans le cadre du projet S.C.S.D. [2] . Le projet S.C.S.D. a demontré qu'un concept operationnel basé à la fois sur l'approche systémique et la notion de performance, était bien mieux adapté que les méthodes traditionnelles pour répondre aux besoins tant qualitatifs que quantitatifs des administrations scolaires.

La notion de performance a permis de tirer pleinement parti des ressources de l'industrie canadienne pour le développement d'un système de construction (actuellement en application) intégrant les sous-systèmes suivants:

(1) Structure
(2) Chauffage-Ventilation-Climatisation
(3) Plafond-Eclairage
(4) Cloisons
(5) Distribution des Services Electriques-Electroniques

La communication traite de la stratégie développée pour chacune des étapes du projet, des moyens mis en oeuvre et des résultats obtenus.

La communication couvre également:

- le contexte specifique au projet,
- les principales études (des besoins des utilisateurs à l'évaluation des ressources) ayant servi de base à l'établissement des exigences de performance,
- les exigences de performance établies dans le but de définir les problèmes pour lesquels une solution était recherchée,
- les critères définis afin de qualifier et quantifier les niveaux de performance requis, et
- les techniques d'évaluation utilisées durant les trois principales phases, soit pendant la période d'appels d'offres, au cours de la phase consacrée à l'evaluation des soumissions et durant la phase dite "de développement". Ces techniques ont été mises en oeuvre afin d'evaluer les systèmes de construction au niveau de leurs sous-systèmes et en tant qu'ensembles intégrés.

Key words: Bid evaluation; building systems; criteria and tests; educational facilities; life cost; performance specifications; prototypes; strategy; systems approach; S.C.S.D., R.A.S.; technology and feasibility; user needs.

1. Introduction

The R.A.S. Project was initiated in Montreal in late 1966 by Montreal Catholic School Commission with the participating support of Educational Facilities Laboratories.[1]
The Montreal Catholic School Commission, the city's largest schoolboard, has under its jurisdiction a population of approximately 230,000 students and is operating on an average budget of $130,000,000.
The construction program (2,000,000 sq.ft.) is presently under implementation.

2. The Problem and the Approach

What originated R.A.S.? It was the recognition of "the problem" by some Montreal Schoolboard Commissioners. In a nutshell:

- the inadequacy of traditionally accepted methods to provide educators with appropriate and adaptable school facilities, within limited financial boundaries, in order to fulfill a mandate. This mandate, as expressed in sociological terms being to maximize the potential of our youth in order to reach the objectives of society.

A general approach to the problem had already been successfully experimented with in California through the SCSD Project[2] , its substance being the adoption of the "Systems Approach" as a position both for viewing the problem and trying to solve it, and the "Performance Concept" as a means to achieve the objectives subsequently defined. I could not agree more with Michael Brill[3] who has stated:

> "If we could find a way of assuring a good fit, (physically, psychologically and socially) between users and their buildings and communities, we could assure the user's satisfaction with that environment. And so we have turned to a form of "market research", finding out what users need and want through the performance concept within the Systems Approach, helping decision makers design and procure buildings and communities responsive to these needs and wants. If user needs are explicitly stated, and form the value structure of the design brief, and user satisfaction is both the goal and the basis for post-facto evaluation of the results, we ought to be able to assure a "good fit", a useful social instrument and a healthy market."

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[1] Educational Facilities Laboratories, Inc., (E.F.L.) is a nonprofit corporation established by the Ford Foundation to help schools and colleges in the United States and Canada with their physical problems by the encouragement of research and experimentation and the dissemination of knowledge regarding educational facilities.

The problem is dual: it implies at one level a "delivery (or generating) system" - the software; and at another level, the actual hardware which must produce an "environmental system." [4]

Educational facilities are generated by a complex delivery system consisting of the following parts (or sub-systems):

(1) The Schoolboard Educators/Administrators (Owner-User),
(2) The Designers (Professionals),
(3) The Building Industry (in general terms).

These parts are dynamically involved in the Leibnitz sense.

The acceleration of change, so characteristic of our time, has offset the balance of this classical trio which presents all the characteristics of a "flow system." In undertaking the taskof helping this system regain its lost equilibrium, without increasing its entropy, we had to deal with ways and methods of gathering, interpreting and conveying information, as well as with the very content of information and its transformation means.

In order to accomplish our task we had, first, to study the behavior of this system and its components, our primary concern being the ultimate output of the said flow-systems: the transformation of the Owner-User information by the Industry and the Designers into a "schoolplant."

The schoolplant was approached as being a system by itself, defined as an environmental system, whose various integrated sub-systems perform static or active functions in order to create a specific environment. In this case the environment is instrumental to:

(a) pedagogical activities (the teaching-learning process),
(b) the ancillary services supporting the teaching-learning process.

This system could be located between the first and second levels of Boulding's [5] suggested hierarchical classification.

3. General Strategy

A general strategy could then be outlined:

3.1. Harness the human and material resources of sub-system No. 3, the Building Industry:
To develop a comprehensive and flexible building system, of the open type, part of it to be achieved through mass production of building sub-systems tailored to specific requirements.
Thus to provide sub-system No. 2 - the Professionals (Designers) - with adequate building components, allowing them to design educational facilities meeting the recognized needs of sub-system No. 1 - the Owner-User.
Both sub-systems, the Professionals and the Industry, to be supplied with proper information stating the Owner-User needs and requirements in usable terms through adequate vehicles.

3.2. Using the Performance Concept as an approach and Performance Specifications as a means (content/vehicle), the educational facilities to be dealt with were to be clearly defined, and their relevant problems stated with precision. Subsequent performance criteria (as well as tendering rules) and their control or evaluation methods were to be selected or established.

3.3. To offer incentive to the industry and to allow for mass production, a minimum construction volume had to be guaranteed, consisting of both elementary and comprehensive high schools. Briefly, the construction system was to be applied to schools ranging from two to four storeys and amongst the most restrictive contextual constraints, a three-hour fire rating, as required by Montreal code, was to be respected throughout to protect the structure.

3.4. Selected building sub-systems, tailored to the user's need and lending themselves to mass production through industrialized methods, could be considered, provided they were conceived for mutual integration and compatible with other sub-systems implemented in the traditional way.

3.5. Considering the timing constraints and the scope of Research and Development work to be undertaken by both R.A.S. staff and the industry, the projected building system had to be narrowed down to only 5 determinant sub-systems essential to priority objectives fulfilment:

(1) Structural
(2) Heating-Ventilation-Cooling
(3) Ceiling-Lighting
(4) Internal Space Subdivision
(5) Electric-Electronic Distribution

4. Implementing the Performance Concept

The Performance Concept was instrumental in achieving the Project's ends: restoring the "flow-system" and developing a generic "environmental system."

The Performance Concept path was followed throughout its hierarchical levels:

> from user needs and requirements up to Performance Specifications, while determining Performance Requirements and Criteria, and establishing proper evaluation methods.
> (Kushner [6] and Wright [7])

However, the implementation of the Performance Concept depends on the recognition of a double challenge:

> predicting the final outcome (product) within reasonable limits, and weighing those factors essential to obtaining the desired (and predictable) output.

As stated by N.B. Hutcheon [8] :
"the ability to predict is the firm basis for all rational design."

While both the users and the hardware are subject to known fixed contextual constraints, most of human behavior (and its implications) as well as hardware performance have to be predicted. Fixed contextual constraints are those which cannot be modified; they are either of a permanent nature (e.g. climate), or while of a temporary nature, nevertheless prevail at the time of implementation (e.g. economic factors, state of the art, regulations,etc.).

"Intra-muros" behavior of the user, the one we are concerned with, is a complex phenomenon still partly escaping our comprehension (black box) and gives the measure of the formidable challenge to be accepted.

At another level, the Hardware-knowledge is closely related to specific physical implementation conditions. Once these conditions are removed from the prescriptions, prediction becomes the prevailing factor for the task of selecting or establishing Performance Requirements and Criteria with their relevant evaluation methods.

Considering the magnitude of the tasks involved, the knowledge and expertise it requires in various specialized fields, it is obvious that a mandate such as the R.A.S. Project could only be fulfilled by a thoroughly integrated team pooling academic knowledge and practical experience.

5. Building a Basis for the Performance Specifications

Using the 'Performance Concept" approach as a means, a comprehensive teaching-learning process survey was conducted to identify users' needs and requirements, with a dual purpose:

(1) to provide the designers with a bank of intelligible and usable information (thus trying to bridge the well-known communication gap between educators and designers), and
(2) to establish the necessary material from which Performance Requirements could evolve.

In short, educators were required to transmit the "for whom", "for what", "why" but not the "how to".

In addition to the teaching-learning process survey mentioned above, users' needs and requirements were scanned in 5 other major areas:

(1) environmental control,
(2) school operation and maintenance,
(3) first and final cost of a school plant,
(4) educational trends surveyed in an attempt to distinguish a projection of future needs, and
(5) flexibility (spatial adaptability).

Parallel studies completed the basis necessary for the development of Performance Specifications, such as:

- analysis of the generic functions performed by the schoolplant's built elements,
- survey of recurrent hardware interfacing problems (compatibility, dimensional co-ordination, etc.).

6. The Performance Specifications

At first, Performance Specifications were outlined for the building system as a whole; its "exterior aspect".

In order to meet our main objectives, it was decided that the building system should have the following main characteristics:

(1) maximum obstacle-free space to allow for spatial adaptability,
(2) operational flexibility for components participating in the environmental control, and
(3) design flexibility for the user.

The desirable performances were weighed against:

(1) a cost ceiling,
(2) an anticipated building and operation cost reduction,
(3) the industry's resources availability, and
(4) the extent of time available both for the preparation of Performance Specifications and the subsequent industry Research and Development activities to be accomplished during and after the tendering period.

We were then in a position to study in detail the "internal aspect" of the system, and start preparing preliminary Performance Specifications for each of the sub-systems.

Performance Specifications were to be documented under two categories, depending on whether they were applicable to the system as a whole or to each of its sub-systems.

(1) General Performance Specifications covering:

- overall integration,
- overall flexibility,
- modular coordination,
- dimensional criteria,
- provisions for coordination with non-industrialized sub-systems, and
- aesthetics

(2) Individual Performance Specifications, for each of the sub-systems, dealing with:

- functions to be performed in correlation with assigned criteria (dimensional, technical design, quality, etc.),
- interfacing with each of the other sub-systems,
- coordination with non-industrialized sub-systems,
- flexibility, and
- operation and maintenance.

Our concern with overall integration was motivated by the risk reduction philosophy we followed. Total integration was made mandatory for bidders. Bidders were free to integrate their respective sub-systems in as many systems as they could manage, providing that interfacing details were submitted for every single combination. Another reason motivating this request was our aim for maximizing the systems' performances while avoiding over-investment of all kinds. The quality of the tendering results has justified the emphasis we placed on total integration.

7. Major Requirements and Criteria Covered by Performance Specifications

7.1. Environmental Control

(a) Atmospheric

Performance Criteria were related to 8 families of premises defined in terms of density of occupation and nature of task performed. Technical data were provided to bidders, such as:

- outdoor conditions,
- thermal factors (to be implemented later in the design of non-system exterior envelopes), or
- internal heat gains due to equipment or occupants.

(b) Lighting

Lighting Criteria were related to specific visual tasks performed in a schoolplant. The Ceiling-Lighting sub-system was sub-divided into 4 assemblies (PE-1 to PE-4) corresponding to rooms having a common core of visual requirements. The PE-1 assembly (academic activities) had to satisfy the Visual Performance Index (V.P.I.) developed by Dr. H. Richard Blackwell [9], the index being 63.0.

(c) Acoustics

Acoustical control was approached as a whole, the 5 sub-systems bidders (within each system) being collectively responsible. It should be noted that the sound absorption required in the Performance Specifications had to satisfy the criterion corresponding to Sound Transmission Class 40 (S.T.C.). A set of acoustical tests was selected ranging from rating of material to full scale testing of a mocked-up classroom.

Background noise generated by both the operation of the lighting and the mechanical sub-systems was to be maintained between minimum and maximum N.C. levels.

We were most obliged to the work of SER [10], for it provided us with a bank of valuable information concerning school environmental control.

7.2. Flexibility,Adaptability,Versatility

(a) Structure

The structural sub-system had to be designed to create large spaces free of any obstacles.
Freedom in the change of direction of spans was requested for design flexibility.
Conception of the system geometry had to allow for future horizontal expansion.

(b) Internal Space Subdivision

Partitions ought to be moved every 20" in either direction.

(c) Heating-Ventilation-Cooling and Ceiling-Lighting

Both sub-systems' concept had to allow for rezoning of spaces to be serviced.

(d) Electric-Electronic Distribution

Distribution of Electric-Electronic services was to be ensured by means of movable service "columnettes" relocatable on a 20" x 20" grid. These columnettes had to be plugged to a network of nodal junction points to be located within the floor-ceiling "sandwich" space.

This sub-system represented a new approach to Electric/Electronic services distribution and Performance Specifications had to include guidelines (a less orthodox implementation of the Performance Concept), to help manufacturers visualize the concept.

7.3. Interfacing and Dimensional Coordination

A planning grid was to be implemented, based on a 20" x 20" horizontal module and a 8" vertical module.
Maximum acceptable structural deflections and cambers were defined.
Interfacing rules based on international modular conventions were provided to bidders for pre-coordination of jointing and dimensional deviations.
Technical data were identified and requirements established to allow for interfacing with non-system components such as exterior envelope and stairs, as well as with non-system services.

7.4. Serviceability and Durability/Reliability

Sets of Performance Criteria covered:
- resistance to vertical and horizontal forces for all interior components, and
- resistance to surface damages such as impact, corrosion, abrasion, for all components.

7.5. Structural Sub-System

In addition to Performance Criteria previously mentioned, the structural sub-system's specifications included sets of criteria covering: structural safety and serviceability; uniform live loads and concentrated loads; Standardization of dimensions; types and number of structural components.

7.6. Fire Safety

In addition to a three-hour throughout fire protection required for the structure (by regulations), all interior finishes had to satisfy "flame-spread" and "toxic emanations" Performance Criteria.

7.7. Aesthetics

It could be of some interest to outline the way "aesthetic requirements" were handled for they cannot be quantified and therefore require evaluation methods based on empirical expertise.

Basic performance guidelines were implemented and backed up by a rule establishing our right to be sole judge in matters of evaluation of compliance with aesthetic requirements.

Adaptations or changes could be requested.

Guidelines stressed such points as:

- expedients or camouflage to be avoided,
- components traditionally concealed to be exposed wherever possible,
- components to be differentiated,
- forms to be compatible (geometry),
- clarity, cohesion, unity, contrasts and balance (of forms, textures and colours),
- imitation finishes ruled out, etc.

8. Evaluation Techniques

8.1. Theoretical (or guide) Plans

In addition to normal technical documentation, bidders were to demonstrate the application of their respective sub-systems to four theoretical school models, whose plans were part of the Performance Specifications. This allowed for an evaluation to be made of the practical solutions offered and also provided for further comparison of the various proposals.

8.2. Cost of Performance

(a) One of the aims of the R.A.S. Project was to achieve a construction system at a price below the Target Cost, while attaining the objectives and complying with the requirements of the Performance Specifications. Any bid above a Cost Ceiling based on "traditional" construction cost prevailing in Montreal, was to be rejected.
The Ceiling and Target Costs were expressed in specific manner for each of

the possible combinations of the floor/ceiling sandwich space thickness which could be used by the bidders. A credit and penalty clause was developed based on the estimation of extra expenditure required for every 8" vertical module increment.

(b) Another correction factor was established for the mechanical room and vertical duct spaces used by the bidders.

(c) The evaluation of bids procedure also covered the estimation of the system's life cost. For each sub-system, the first cost, operating and maintenance costs were converted into an annual life cost through a capital recovery factor based on its expected life.

(d) The operations cost due to spatial transformation was estimated from an exercise requested of all bidders. It was based on a typical area, undergoing major spatial changes during one year, the resulting estimation being converted by the means of the weighting factors previously used for quantity estimation.

8.3. Integration and Flexibility

The Performance Specifications included requirements calling for the fabrication of prototypes to be assembled into full size mock-ups and erected during the development phase, the purpose of which was to allow for full scale:

- performance testing,
- interfacing evaluation,
- simulation of spatial changes (moving of partitions, re-zoning of Heating-Ventilation-Cooling and Ceiling-Lighting,
- moving and re-zoning of Electric-Electronic services.

8.4. Evaluation of Structure

Applicable serviceability and safety tests (loading, testing of joints, load distribution, high-tensile bolt tightening, etc.) were to be selected from a pre-established list (referring to existing standards) according to the nature of the submitted structures. As an alternative evaluation method, analysis could be, when applicable, substituted to testing.

8.5. Standards

In general, testing methods were based on U.S. Standards (A.S.T.M. and F.S.) and Canadian Standards (C.S.A. and D.N.D.).

9. Staging of Evaluation Procedures

Staging of evaluation procedures reflected the established quality assurance strategy.

9.1. A mid-term review took place during the six-month tendering period; its primary objective was to evaluate the bidders' preliminary proposals to ascertain that Performance Specifications were properly interpretated.

9.2. The Ceiling-Lighting sub-system's V.P.I. index, see Par 7.1. (b), was conducted prior to submission of proposals.
In 1967 insufficient data were available to assess the potential hardware which could satisfy this relatively new performance criterion.

9.3. All major testing of selected system took place during a post-bid development phase.
In addition to evaluation procedures, called for in Performance Specifications,

provisions allowed for complementary testing to be defined only during development phase, thus taking into consideration the very characteristics of the submitted hardware.
A typical example would be the Heating/Ventilation/Cooling unit. Analysis led to suspicion that the selected unit, because of its very compact configuration, could cause a stratification phenomenon (layers of cold and hot air). Thus an additional test was requested which resulted in modifications, such as readjusting the location of air-intakes and the position of fans.

10. Conclusions

Our team's work has been rewarded by the quality and ingenuity of the building systems developed for the project. As a whole, our objectives were met beyond expectations - the level of performance of the selected hardware is well above the minimum threshold of acceptability.

Of course we had our frustrations. Some "political changes" did offset our schedule forecasts, which seems to indicate that when undertaking such a venture and trying to predict the generating flow-system's output, contingencies such as "politics" ought to be integral parts of the planning parameters.

Without fear of appearing too dogmatic, I could say that undertakings such as S.C.S.D., R.A.S. and other similar projects, have shown that the Performance Concept is indeed the road to follow if the ultimate goal is to provide the educational process with an adequate built environment. Furthermore, I do believe that each new experience is bringing us closer to our ultimate (holistic) goal, for, as stated by Jonathan King[1] "the next step might be for someone to write a performance specification for a schoolhouse rather than a component of the schoolhouse." 1.b.

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[1] Jonathan King is the former Vice-President of Educational Facilities Laboratories, Inc.

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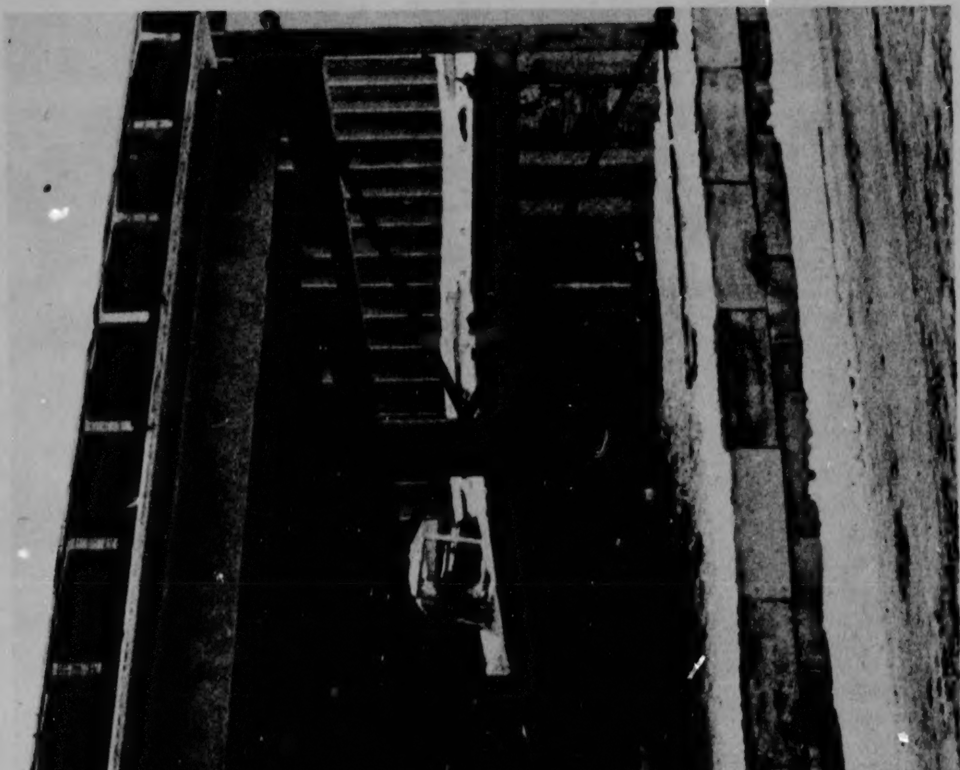

Fig. 1 Mock-up of Structure used during Development Phase for structural tests.

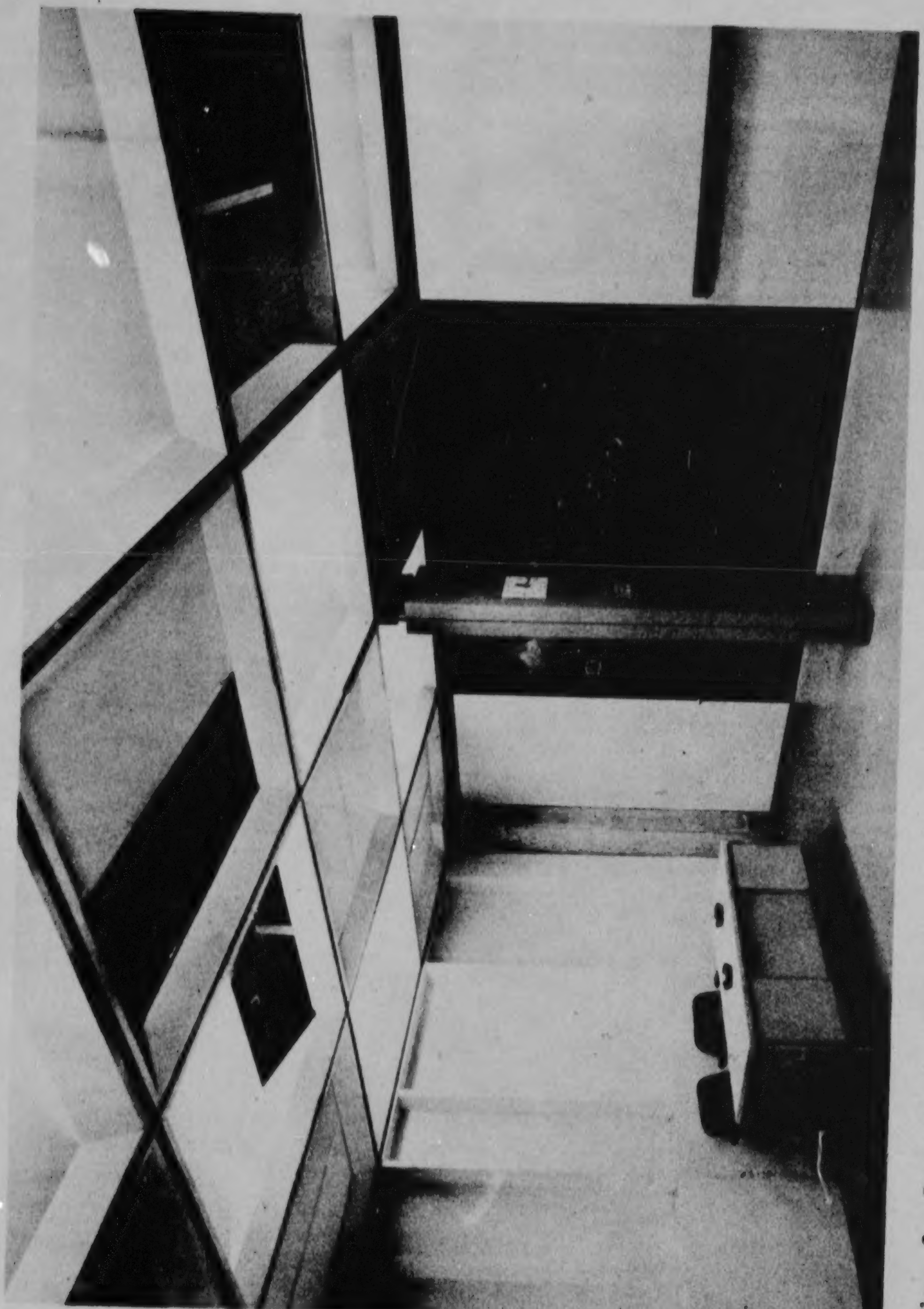

Fig. 2 Same mock-up equipped (after structural tests) with prototypes of interior sub-systems for testing of interfacing and flexibility.

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

The Development of Performance Criteria for University Facilities

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Since its inception in 1962, the State University Construction Fund has been responsible for the planning, design and construction of campus facilities for the State University of New York. It is estimated that as of September 1971, the Fund has completed, or placed under design or construction, facilities costing 2.31 billion dollars. In concert with this large-scale effort, the Fund has undertaken the development of performance criteria for its physical facilities in two groupings - Environmental Performance Criteria and Functional Performance Criteria. It is contemplated that criteria in these two areas will be synthesized into a third area of criteria for Construction System Performance upon completion of research in progress. Difficulties in generating industry wide acceptance of measurable performance criteria has lead to the exploration and development of a variety of means of communicating Fund requirements to the design professionals who prepare plans and specifications for university facilities. These interim approaches to communication of performance requirements include: State-of-the-Art documents, specification statements, administrative procedures, design development process descriptions, space planning and design criteria and check lists. Much remains to be done in the direction of more precise and comprehensive communications within the construction industry with measurable performance criteria a mainstay of this goal.

Depuis sa création en 1962, le Fonds de Construction d'Universités d'Etat est responsable pour la planification, l'étude et la construction d'installations universitaires pour l'Université d'Etat de New York. On estime que, jusqu'à septembre, 1971, le Fonds a complété ou mis en projet ou en construction des installations coûtant 2,31 milliards de dollars. De concert avec cet effort à grande échelle, le Fonds a entrepris de développer des critères de performance pour ses installations matérielles sous 2 rubriques - critères de performance du milieu et critères de performance fonctionnelle. On espère que les critères de ces deux domaines seront synthétisés en un troisième domaine de critères pour le fonctionnement de systèmes de construction après que les recherches en cours auront été terminées. Les difficultés rencontrées pour persuader l'industrie d'accepter, en large partie, les critères de performance mesurable ont poussé à l'exploration et au développement d'une variété de moyens de communiquer les exigences du Fonds aux professionnels qui préparent les plans et spécifications des installations universitaires. Ces démarches intérimaires pour communiquer les exigences de performance comprennent: des documents sur "l'Etat de l'Art", l'énoncé de spécifications, des méthodes

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administratives, des rapports sur l'avancement d'études en cours, l'organisation de l'espace et des critères d'étude et des listes de contrôle.

Key words: Acoustical environment; administrative procedures; communication; environmental criteria; functional criteria; interior finishes criteria; luminous environment; measurement; outdoor lighting criteria; performance criteria; process description; university facilities.

1. Introduction

Since its establishment by the New York State Legislature in 1962, the State University Construction Fund, SUNY, a public benefit corporation, has been responsible for the planning, design and construction of campus facilities for the Colleges and University Centers for the State University of New York. By 1975 the University will have an enrollment of over 230,000 students, an increase of more than 180,000 in 13 years. It is estimated that as of September 1971, the Fund has completed, or placed under design or construction, facilities costing about 2.31 billion dollars.

The Fund has undertaken to accomplish these tasks by contracting with architects, engineers and building contractors from the private sector to plan, design and construct sitework and buildings on the 30 geographically separate campuses within the State University System. For the most part, the work administered by the Fund has followed the "conventional" public works practice in the United States of: (1) program development by the owner; (2) planning and design by the firms of Architects and Engineers as the owner's agents: (3) public bidding on price, and (4) construction by building contractors who are monitored by the owner and his agents. In this context, performance criteria, generated by the State University Construction Fund as the owner, become part of the program development activity. These performance criteria are designed to be transmitted to the Architect for incorporation into the plans and specifications to be used in the construction of individual projects.

Recently, the Fund research into more systematic and industrialized facilities delivery has resulted in a concern for criteria applicable to building components or subsystems. The Fund criteria under development fall into two groupings, environmental and functional. The functional criteria include space planning or material related performance criteria. It is contemplated that criteria in these two areas will be synthesized into a third area of criteria for construction systems performance following completion of current systems building investigation.

2. Developed Criteria

2.1 Environmental Performance Criteria

As one of the two groupings of developed criteria, environmental performance criteria have been divided into three basic areas, the luminous, thermal and acoustical environments. All of these are concerned with the performance of interior space.

(a) Luminous Environment

The luminous environment research is based upon the idea that lighting for each space or area in a building should satisfy the needs of the activities occuring in that space. Since these activities may vary in both the short and long range, the lighting should be flexible enough to accommodate these changes. The satisfaction of this theory requires a more complicated definition of criteria than merely the establishment of foot candle levels to be provided on work or activity surfaces. In fact, before any criteria can be applied, it is necessary to identify the activities taking place in the space and determine their general lighting needs. This understanding has led to a two phase approach to the resolution of this problem. The first phase is the description of the "process" of lighting design and an attempt to integrate this "process" into the larger architectural design process so that lighting considerations are acted upon during the process rather than as an afterthought. The second phase is the development of lambert-per-square-foot lighting budgets related to the activities to be accommodated in various spaces. These budgets are expressed in the form of "curves" which will be completed by the owner/architect for each space to receive this design treatment. The designer then devises a lighting solution which fulfills the activity needs within the criteria established by the lighting budget. The report presenting this material is under development.

(b) Thermal Environment Criteria

Thermal environment criteria are being studied at this time. The state of the art is to be evaluated and the nature of the procedure necessary to integrate criteria established for the thermal environment into the larger overall design process is to be investigated. Criteria will be developed from available sources for temperature, humidity, air changes, etc., and related to a list of over 200 more or less standardized space classifications from which most State University of New York Buildings are programmed. The spaces on this list are divided into categories such as offices, classrooms and biological science laboratories and include such space names as: financial office, home economics classroom and biology laboratory.

The development of this process/criteria approach is concerned with the thermal requirements of the human activities expected to occur in this variety of spaces. Levels and methods of control of the atmospheric environment, both natural and mechanical, will be considered.

(c) Acoustical Criteria

The Fund's acoustical environment controls which are under development have the same process/criteria base. Acoustical criteria have been developed for the spaces or space categories on the SUNY standardized classification list mentioned above. These criteria are concerned with: a. ambient noise levels; b. reverberation times; c. anticipated noise levels d. impact and structure-borne sound; e. room acoustics; and f. special considerations. Along with these criteria sheets, it is intended to provide the architect with some technical information describing the relationship between basic design considerations and the achievement of the levels of performance established by these criteria. The objective is to help the architect to deal with routine considerations as well as to be able to identify those situations which require the assistance of acoustical consultants. A typical criteria sheet is presented to illustrate the level of development.

Acoustical Criteria Sheet No. 145

Biology Lab
Botany Lab
Genetics Lab
Microbiology Lab
Physiology Lab
Zoology Lab

SUNY Space Classification: 43 BIO

1. Recommended Ambient Noise Levels: Noise Criterion contour of NC-30 to NC-35
2. Recommeded Reverberation Times (in seconds): Less than 0.8 at 500 Hz. Design to this value or below for unoccupied room condition.
3. Other Room Acoustics Considerations: Not usually a problem. Adequate breakup provided by wall-hung cabinetry and equipment throughout room. Sound-absorbing treatment over entire ceiling area generally adequate for room noise control.
4. Sound Amplification Requirements: None

5. Noise Levels Likely in this Room (in dB re 0.0002 dynes/cm^2):

Octave Band Center Frequency (Hz)

	63	120	250	500	1000	2000	4000	8000
Equipment	65	70	73	75	72	69	65	61

6. Impact and Structure-Borne Sound: Moderate - as generated by normal room usage. Certain laboratory equipment may cause severe vibration problems. Other equipment may need to be vibration free. Individual equipment should be studied. Typical laboratory activity is moderately susceptible to disturbance from surrounding areas.
7. Special Considerations: Programmed uses of the particular laboratory should be reviewed to determine possible need for more specialized control of the acoustical environment for critical experiments. Equipment to be installed should be considered from standpoint of noise generation.

Research planned for the future seeks to synthesize these interior space criteria for the luminous, thermal and acoustic aspects of the environment. For example, increased lighting levels can generate additional heat which requires additional air-conditioning which makes more noise and necessitates additional acoustical treatment. In theory it should be possible to establish numerical relationships between these three aspects of the environment; however, the development of a "process" with a device for evaluating "tradeoffs" may be more possible to achieve.

2.2 Function Criteria - Space Planning and Materials

The second group of criteria developed by the Fund is more concerned with the functional performance of spaces and materials. The criteria related to space planning have been developed for facilities for the physically handicapped, outdoor nighttime lighting, and health and physical education facilities.

(a) Handicapped

The Fund's criteria for the physically handicapped are directed towards the incorporation of these specialized facilities in all university buildings. Identification of the problems and concerns of the handicapped as they relate to functioning in a university environment are translated into physical concerns such as space required to maneuver a wheel chair, door sizes, ramp requirements, the need for hand holds etc. The criteria to be met are described and illustrated. In addition a checklist of key items to be considered by the designer is included.

(b) Outdoor Lighting

The outdoor nighttime lighting criteria developed by the Fund take the form of a state-of-the-art-document, describing such areas of concern as orientation and identification, security and safety, and character and atmosphere. Definitions of use and design principles and performance objectives are identified for the outdoor areas treated such as roadways, footpaths, pedestrian precincts and sports facilities. Checklirts are provided for the designer within the context of a network which describes the design process.

(c) Health and Physical Education

Health and Physical Education facilities are treated by the Fund in a building-type study which identifies criteria to be achieved in the form of specific diagrams and accompanying text. This approach to communicating criteria is very direct and limits the flexibility of solutions. The need to standardize, which derives largely from the requirements of intercollegiate athletic competition, provides a justification for this approach. A checklist format is used to communicate much of the information.

(d) Concrete

The Fund's criteria for concrete and concrete aggregate are material-related criteria which are to be presented in two volumes. Volume I concerns criteria related to the design of cast in place, precast, and prestressed concrete. Most of the material is state-of-the-art information in a checklist format. Some computational-based criteria in the form of mix formulas and loadings are provided. Volume two is to be a visual (in color) and descriptive inventory of fine and course aggregates available in New York State. Case study and network process descriptions are to be provided to illustrate the method of locating and opening inactive or new quarries.

(e) Interior Finishes

Performance criteria for interior finishes (floors, walls and ceilings) are perhaps the most fully developed undertaking in the area of materials performance. The Fund sought to develop generic tests applicable to interior finishes and to establish performance levels against these tests for the spaces on the SUNY Space Classification list. The intent was to be able to compare "terrazzo to tissue paper". In order to simplify this initial effort, the spaces on the list were sorted into twenty-two categories having similar characteristics. Performance requirements for each of these categories were established against sixteen test methods. These performance levels were assessed against available information and are subject to verification and adjustment in practice. The sixteen tests as described in the copyrighted project report are as follows:

- Determining Resistance to Fungi, with Nutrient - A suspension containing a mixture of several types of spores is sprayed over test specimens mounted on a suitable nutrient. After incubation in covered dishes kept at 28° to 30°C for 21 days, the specimens are examined for the presence of fungi on the surface, and rated visually.
- Determining Resistance to Fungi without Nutrient - Spores from freshly prepared cultures are swabbed over the surface of the test specimens. The inoculated specimens are kept in a desiccator which contains standing water for 28 days at 25°C at the end of which period they are rated visually in five groups.
- Determining Resistance to Chemicals - A sample of the surface or finish under test is immersed or covered with a test solution or hung in its fumes for the specified time duration. After being removed, dried and conditioned, the sample should be weighed and its length, width, and thickness measured. These post-treatment values are compared with original values and the sample is visually examined. The following kinds of exposures were selected and are identified as individual tests: (3) reagents (biological areas), (4) acids and alkali, (5) strong solvents, (6) foodstuff derivatives, (7) lactic acid, and (8) water with detergents.
- Determining Resistance to Abrasion - A specimen or a standard panel coated with the test finish is mounted in a Taber Abraser with 1000 gram weights on the wheels. The loss in weight or wear index shall be determined as specified in standard tests which are described in the project report.
- Determining Resistance to Impact by Falling Ball - A specimen of the material or test panel bearing the finish is mounted in a supporting frame with the finish side toward the ball. The ball is released magnetically to strike the specimen from successively increasing heights until failure occurs or a height of 10 feet is attained.
- Determining Resistance to Scratching - A set of 16 standard drafting pencils of the same brand, but of varying degree of hardness (6B thru 8H) are used to determine which pencil is harder than the surface of film under test. Any marring, scratch or indentation noticeable indicates that the pencil was harder than the film.
- Determining Resistance to Hot Water or Steam - A specimen or test sample of a coating applied to a steam - resistant substrate is kept for 24 hours in an atmosphere of 80°C and 100% relative humidity. It is then removed, examined, and placed in an oven at 80°C for a second 24 hour period with only ambient humidity. Each two days of exposure, the first one to wet heat and the second one to dry heat, constitutes one testing cycle.
- Determining Washability - All paints and coatings are applied with a white enamel under coat while all other materials are merely mounted in the testing device in the plane of the glass plate of the standard method described in the project report. The panel is scrubbed with a brush for the required number of cycles (double strokes). After each 100 cycles, the test panel is observed carefully for evidence of breaks, wear, or delamination of the surface film.

- Determining Slip Resistance by Static Means - A constant load of 75 pounds is applied to the test surface through a 3-inch-square leather-shod steel block. The angle of application of this load is varied to find the critical angle. This critical angle is then converted graphically into the coefficient of friction.
- Determining Slip Resistance by Dynamic Means - A mechanical shoe, forming the lower end of a compound pendulum is so arranged that a test piece of leather or rubber heel material can be attached to the underside of the shoe. The pendulum, released from a fixed predetermined height, is allowed to sweep over the surface being tested. A pointer attached to the framework records the height to which the pendulum swings beyond the floor specimen after contact. This reading is converted into a coefficient representing the non slip characteristics of this combination of materials.
- Determining Resistance to Fading - A sample is exposed to an ultra-violet light source in a device similar to commercially manufactured meters designed to measure fading. At regular intervals, the specimen is removed and compared with an unexposed sample to determine what changes, if any, have occurred in the appearance of the sample.

With the tests and tentative levels of performance for floors, walls, and ceilings established, the Fund undertook to familiarize the industry with this information. Preliminary and informal discussions with architects indicated their interest in being able to match in a measurable way the requirements of an owner, as expressed in these performance criteria, with interior finish materials which could satisfy these requirements. Discussions with persons involved with commercial dissemination of information retrieval, indicated that if performance levels of interior finish building materials could be obtained from manufacturers, it would be possible to use data processing equipment to store and retrieve this information. In this way, architects and other design professionals would be able to locate those materials meeting performance standards established by an owner.

At this point a series of informal discussions were held with about ten representative manufacturers of interior finish materials to determine their interest in participating in a program which would involve the evaluation of their own materials using the tests developed for the Fund. The results of these discussions were inconclusive and generally not encouraging. One manufacturer is presumed to have evaluated his materials, however no information has been released. Two manufacturers exhibited interest and raised some useful points with regard to the technical aspects of the tests and it appeared that it would be possible to resolve these issues. The other manufacturers have not aggressively pursued the offer of an opportunity to participate in such a program. Based upon this response, coupled with limited resources, the Fund has determined not to independently carry this undertaking further. Present plans contemplate an informal effort to encourage other institutional owner builders to join together with professional and industry associations to pursue the objective of establishing measurable performance criteria and the matching of available materials to them.

This experience illustrates the difficulty of generating common acceptance of this much discussed concept of measurable performance criteria which have general application. The conclusion of the Fund's Research and Development unit is that broadly-based support is necessary but difficult to achieve considering the diversity of building programs, needs, jurisdictions and geographical locations. As a consequence an approach has been formulated to explore and to develop several means of communicating requirements to the design professionals who prepare the plans and specifications for university buildings.

3. Interim Approaches

Several interim approaches have been developed to achieve this communication including state-of-the-art studies, specifications, procedures, process descriptions, space planning and computational design criteria, check lists and measurable performance criteria for materials and components.

State-of-the-art studies seek to identify the most current information about a particular subject of interest allowing the architect or engineer to use this information within the context of his best professional and responsible judgment. The Fund's research in cast in place, precast, and prestressed concrete falls into this category.

Specification type information is usually developed in response to field experience and indicates that certain types of materials or installations should or should not be used under identified conditions. These specification statements are presented in the form of individual Program Bulletins which cover a general area such as heating, ventilating and air-conditioning or in some cases specific subjects. These bulletins are regularly updated as conditions change and new technology evolves.

Administrative procedures are designed to monitor the work of design professionals, in such areas as; schedule, budget, conformance to program and response to the kinds of controls being discussed.

Process descriptions are effective devices in helping the architect and engineer to achieve a controlled result without imposing unnecessarily on his creativity. These processes describe a series of steps or procedures to be gone through within the design process. The Fund's work with the luminous environment is an example of this appraoch.

Space planning and computational design criteria represents a more formal effort to direct a particular result. Space planning criteria usually take the form of drawings or diagrams with explanatory text which describe the desired result. The Fund's Criteria for the Physically Handicapped and for Health and Physical Education Facilities are examples. Computational design criteria are equally specific and establish performance levels in particular spaces which form the basis for design. Examples include acoustical, luminous, and the proposed thermal environment criteria.

Checklists for use by the design.professional recall to mind essential elements to be considered in the design process. Checklists are frequently used in conjunction with process descriptions and state-of-the-art studies. Fund materials presenting criteria for Outdoor Lighting and the Physically Handicapped among others, include checklists.

The development of measurable performance criteria having general application seeks a greater precision, but requires a response from those providing the materials and components of construction. The intensive work in the area of industrialized building is adding a new dimension to this objective. The Fund's work with interior finishes is an example of efforts to apply this approach to the more traditional methods of delivering buildings. Current Fund research in the area of rationalized (systems) delivery of facilities may be of further benefit.

Much remains to be done in the direction of more precise and comprehensive communications within the construction industry. The development of measurable performance criteria is a mainstay of this goal. Cooperative effort is essential if these goals are to be achieved.

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Experience and Lessons from an Innovative Housing Project Using the Performance Concept

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A large low-income housing project of low-rise construction has been completed in an industrialised building system selected by competitive bidding based upon performance criteria written by the architects. Provisional building designs were prepared in advance as part of an innovative community plan and formed part of the guidance in formulating the criteria. Initial screening reduced the number of bidders to three, all of whom had then to be assisted to develop conformity to the criteria. This part of the project demonstrated the need for whole-dwelling performance requirements established nationally.

Examples are given of the ways in which the design requirements of low-rise high-density development influenced the performance criteria. They are the need to park cars beneath 3 and 4-storey construction, the assembly constraints due to narrow pedestrian passages, a need for step-back balconies and terracing, and party floors which meet fire and sound requirements.

Unconventional performance-based specification items were also exemplified. Concrete finishes were prescribed by Munsell classification, and were also required to deter scribbling. Weather-tightness of joints, thermal performance (in some detail), sound insulation and fire were covered.

The bidding procedure required a new sequence and form for contract documents and this is described.

Prototype dwellings had to be built for agreement on quality of finish and to remove difficulties from the assembly process. Some criticisms are made of the inadequacy of preliminary trials which is unavoidable at this stage as present conventions operate, and this is noted as a cause of some defects which later became evident.

Other lessons are identified. The performance approach requires equivalent development of evaluation and testing procedures, and changes in legal and contractual matters. The vital role of building research organisations for monitoring and feed-back is emphasised for the collective learning process of the professions and industry. The relation between responsibility and deficiencies in the absolute state of knowledge for innovational situations is noted. The educational unpreparedness of the industry is emphasised as a barrier and cause of enhanced risk.

Finally, five major factors of building education and administration which need review by governments promoting innovation are identified.

Cet exposé décrit un grand projet de construction industrialisée d'habitaions à loyer modéré, choisi par soumission de dessin de concours basé sur un projet schéma et des critères de performance préparés par les auteurs (les architectes). Ce projet appartient à la catégorie qu'on a appelée construction basse à haute densité, et comprend de nombreuses innovations. Un premier triage avait réduit à trois le nombre d'offres de soumissions. Toutes trois ont eu besoin d'assistance technique pour se conformer à ces critères. Si des critères nationaux de performance pour habitations entières avaient existé, ce processus n'aurait pas été nécessaire.

On donne des exemples de critères de conception de projets et d'assemblage qui devraient faire partie d'un tel système national, ainsi que des critères dictés par l'architecte. La procédure de soumission a exigé une nouvelle séquence et de nouveaux documents de contrat.

Il a fallu soumettre des prototypes d'habitation à une approbation préalable concernant les finitions et l'assemblage. On décrit les risques appartenant à une telle procédure.

On examine le problème de l'évaluation et de la vérification de la performance, ainsi que certains problèmes légaux qui se posent concernant la responsabilité pour des défauts où l'état absolu des connaissances n'est pas suffisant pour permettre de les éviter. On discute les lacunes dans la formation qui rendent l'industrie du bâtiment peu réceptive à l'innovation.

Finalement, on distingue cinq facteurs principaux que doivent prendre en considération les gouvernements qui désirent promouvoir de nouveaux modes de construction.

Key words: Building systems; education; government sponsored research, need for; housing - industrial, innovated, prototype, low-rise-high-density industralization; performance requirements.

Low-rise, high density housing is a form of development which abandons conventions about streets and front gardens so that densities can be reached which are sufficiently economic in terms of land use to avoid having to use high-rise buildings. It has been developed in Britain and Europe largely for low-income housing, though of course it need not be restricted to this category. Its popularity implies doubts about high-rise apartment building for low-income groups on social grounds and a parallel view that proximity to ground level and some form of garden offers better opportunities for good family and community life. Typically schemes combine houses and low-rise apartments, and reach densities of 90-130 bed-places per acre.

We were commissioned by Harlow New Town Development Corporation in 1962 to carry out such a project, amounting to some 480 dwellings. We were specifically requested to use industrialised building so that the Corporation could gain experience of its problems in anticipation of its more widespread use. We had a 22 acre site and a density requirement of about 90 bed-places per acre.

Industrialised building has been most competitive economically for medium and high-rise apartment buildings. A large number of such systems, - more than 200 - had relatively quickly come on the UK market at the time of our commission, and only a very few were relevant for use in the 1 or 2 storey range, and none for the full range of 1 - 4 storeys.

One might have started by selecting one of these few potentially acceptable systems from a catalog. A private entrepreneur would have expected to use his own system. Neither approach was satisfactory in this situation because there were no stated performance requirements which systems had had to meet during their development beyond those of customary regulations for safety and health. Apart from this, none had specifically been developed to meet the design problems of low-rise high-density projects, and were too inflexible architecturally. The client's original intention had been that we would develop a new system, but the upsurge in numbers of systems then coming on the market made this seem superfluous, and a successful system really takes a big effort and a lot of capital to develop.

It was therefore determined that the approach would be as follows:

a. A provisional design would be developed to define the planning and design requirements.

b. Performance criteria would be written so that bidding would be between near-equivalents.

c. Bidders would be expected to demonstrate conformity with performance criteria in advance, and of course the systems would be subject to subsequent test if called for.

d. Preliminary screening would be done to discover which firms were offering systems potentially appropriate, and which of these desired to bid for the project, considering location of plant, current commitments, etc. It was thought that concrete would be the basic material, to simplify fire resistance and sound insulation, and because it seemed likely to give less jointing problems than metal-frame clip-together systems which were the principal alternative. Maintenance would also be minimal, it was thought, and an exposed aggregate could give satisfactory appearance at close proximity.

e. Three bidders survived the screening. A period was then allowed for collaboration between us and them in order to help them get their systems into conformity with the performance criteria and design requirements, so that formal bidding could then proceed.

Our first lesson, then was that industrialised building as a whole suffered for competitive purposes in the lack of comprehensive performance requirements to ensure basic equivalence in the products. The second lesson was that there had been insufficient architectural exploration of high-density low-rise planning to give an adequate feed-back to systems developers about the kinds of flexibilities needed by architects in order to get good social and architectural solutions.

For information, this latter point reflects the fact that in the UK, design of whole communities is usually assumed to be an architectural problem and that the hardware must meet reasonable design needs for this purpose, rather than that the limitations of a particular system should narrowly constrain design freedoms. Over the years since 1962 design flexibility in systems has increased, but it was poor at the time of our project. Incidentally, our performance requirements were being written at the same time as those by Ehrenkrantz for the School Construction System Development (SCSD) project in San Francisco, California, U.S.A.

We experienced some problems in expressing the design requirements within the performance concept.

The following are examples which illustrate the difficulties:

a. The high densities precluded bringing cars to one's door for access and parking if some open space was also to be conserved. The system therefore had to make possible parking below the 3 and 4-storey construction.

b. With many narrow pedestrian passages no components could be large unless a very wide-reaching crane was assumed to be used for assembly, which was seen as an undesirably expensive constraint.

c. Step-back balconies and terracing had to be possible.

d. Party floors had to be available offering proper fire resistance and sound insulation. None existed initially in the systems which were available for low-rise design.

We would now add a requirement about the appearance of roofs as seen from above. We did not do so and regret it.

Much of the eventual specification was conventional, covering works, materials and workmanship, with references to code requirements for loads, Building Research Station Digests, and so on. Unconventional aspects introduced as performance criteria are exemplified by the following:

External finishes: we expected concrete, and we specified by Munsell reference the lightness, hue and chroma brackets we would accept in overall appearance for the desired exposed aggregate finishes.

We required a scribble-deterrent surface.

Weather-tightness of joints was identified as a major factor, and the buildings as a whole were made subject to an overall warranty about exclusion of water.

Thermal performance criteria of the construction (including cold-bridging) were comprehensively described, as were those of the heating system.

Sound reduction between and within dwellings (both for air-borne and impact sound) was specified to be in accordance with the appropriate British Standard code, normally non-mandatory. These code standards had by then become fairly commonplace in conventional UK construction.

Fire was covered in some detail, but the conventional building regulations in Britain are comprehensive and are largely performance-based already.

Competitive bidding for systems was unusual and in the end required five sets of documents, four in advance and one during bidding. The four required in advance were:

1. The general specification, permitting equivalent alternatives.

2. The approximate bill of quantities for roads and sewers.

3. The provisional design drawings.

4. The performance specification.

The fifth were the final contract drawings and emerged as follows. We worked with the three contractors before the final bidding to help them get their systems to match the performance and design requirements. This was an unexpected and revealing operation, for it made evident the gap between the knowledge assumed to be adequate for conventional building and that which is essential for innovation to attain specified performance. It was at times a difficult gap for us to close. The plain fact is that much of the building industry is not educationally or managerially prepared for modern innovative building technology. A requirement for a sound reduction curve having a slope of less than 6 dB per octave is probably still more baffling to building firms than, say, construction in papier mache.

In the final bidding all bids were above the target cost figures by a margin of the order of 15 per cent. One cause was the amount of adaptation necessary to make a single system suitable for one to four storeys. Another was the bidders' own uncertainty about their own costs (innovation tends to cause protective pricing in these circumstances). In the end the cost targets were met by one means or another, with only one significant casualty, a drop from 35 to 30 dB in average sound reduction between rooms internally.

Prototype dwellings were required to be erected to our satisfaction in order to identify the quality of finish to be expected, to adjust details which gave difficulty in assembly, to see how best to coordinate incoming services and protect them from vandalism, and other matters of that kind. These were agreed to be absorbed into the project. Although this was a step towards the development character which is a typical aspect of industrialisation, it falls far short of what is appropriate. In this case no money was available to change any significant details, which is what a prototype should be all about. In fact in our case concrete casting and joinery was already going ahead in quantity. The fact is that the bugs should be out of a system, and known to be out, before it goes into use. The whole procedure of erection, testing and evaluation, feed-back, and modification should be absolutely complete.

In this circumstance it is not surprising that the scheme has not been trouble-free, despite the considerable care taken. Innovation is a frontier operation, especially on this scale. The important thing then is the learning process and its feed-back into the construction community, including the professions concerned. What are the principal lessons we have drawn from this experience?

First, performance requirements going well beyond the conventional coverage of regulations should have been nationally developed and continuously updated as part of the learning process for the industry and the building professions. The client's natural needs are not covered by the usual limitation of the regulatory system to health and safety. That concept should be abandoned for the age of industrialised building. It has proved inadequate to serve the public interest in a period of deeply influential change.

Second, performance requirements require a symmetrical development of evaluation and testing processes, both at the development stage and for checking the completed products.

Third, innovational building and the use of the performance approach requires changes in legal and contractual matters, What may be appropriate for conventional building is certainly inadequate for innovation. It is ultimately a question of who is responsible when something goes wrong. Sometimes the deficiency is in the state of knowledge, and this is one point where national building research organisations have a key position, for in the end, what they do not know, others cannot reasonably be expected to know; and sometimes situations are therefore unpredictable because research may not have got far enough. That is implicit in innovation. But who protects the client? Blame is sometimes difficult or impossible to allocate, and insurance is increasingly difficult for professional people to get. This is an essential matter to clear up if innovation is to be able to continue.

Fourth, the organisation and administration of construction firms is adhering too tenaciously to the processes, attitudes and education standards of traditional building operations. They are not adequate in the modern situations for projects of any significant scale. It was difficult and expensive to introduce our bidders to the technology of performance requirements going beyond conventional regulations, or for them to analyse and anticipate the consequences of their innovation. The education needed for all supervisory grades has to be predictive over the full scope of at least normal performance requirements, and the physical and chemical behavior of materials and components. It should also encompass modern organisation and methods studies.

An outstanding example is the problem of joints. Their design, their construction and their checking is all wide open to faults when one moves from the traditional relatively small and/or moisture absorbent materials like clay, mortar and wood, to the larger and more impervious units of concrete, metal, glass and plastics, prone to form good capillary paths inward for moisture, and dependent on consistently perfect joints able to accommodate the accumulated thermal movements and structural adjustments traditionally distributed over a multitude of junctions of poor capillary character.

To a considerable extent the criticisms mentioned relate to the building professions as well as to the contracting and construction sectors. The ability to appreciate the problems of innovation is seriously inadequate in the education of architects, building engineers, estimators and specification writers, and the widespread deficiency of university-level education for the construction side of the industry is a particularly severe handicap. Educational reform on a major scale among all concerned is an urgent need.

Finally, in a period such as we now confront, when the direction of movement towards industrialisation is constant,(even if the process itself is periodic or erratic), every country requires a building research capability which takes as a principal duty the monitoring of the problems of the change, the identification of them for action by appropriate organisations, and the provision of the knowledge base necessary to implement corrective measures. Since building is a set of complex interactions of many kinds, the research capability has to be comprehensive or it will have fatal blind spots that undermine the learning process. Each sub-system intended to be part of a building has a wide range of related requirements which it must satisfy or be inappropriate for use. Because of the present collective inability of the industry to learn and respond quickly and well enough from fragmented research and monitoring, no country, in our view, has a moral right to encourage or permit rapid or massive innovation without undertaking appropriate educational preparation and arranging for this kind of monitoring capability.

The fact is that the implications of encouraging such a rapid and fundamental change as the industrialisation of the building industry have been inadequately appreciated by governments, and they have responded in an uneven and unsystematic manner to isolated pressures and events. Governments should stand back from this massive process by which humanity creates its physical environment and take a long, deliberate systems-look at what is now required. The principal elements are apparently the following:

a. a collective review of the suitability of education for all the principal participants in building.

b. a comprehensive and adequately researched shift to a performance basis for the regulation of design and construction.

c. a set of standards and criteria for established materials and components which is consistent with performance requirements, and a related system (agrement) for the predictive evaluation of new introductions.

d. a comprehensive monitoring and research organisation. This is the focus of the collective learning process and therefore requires feed-in channels from both the design and construction sectors of the industry, and feed-back channels to the education, regulatory, standards and provisional evaluation systems, as well as to the active design and construction sectors.

e. a review of liability law in respect of design, contracting, construction, and maintenance.

Inadequacies in every one of these four parts of the system gave rise to substantial problems and difficulties in carrying out the project described, and the outstanding lesson for us was the need for extensive reform, based upon seeing the whole as a single, interdependent system.

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

Evaluation Process of Performance and Cost as Applied to Existing Housing Prior to Rehabilitation

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This paper presents a process for evaluating the performance of existing homes and planning suitable changes for users who would like to improve this performance. The process was evolved as a result of field research work in aiding minority group families evaluate their homes. The process is intended to enable a housing advisory group assist families in satisfying their individual User Needs. Given that family's home and their priorities for its improvement, income, and available financing, the process derives realistic rehabilitation choices available. Topics discussed include technical/human housing user interface problems, presentation of information, housing requirement analysis process, individual housing user value rating analysis, housing user financial analysis and the organization of the advisory service. This paper maintains a simple level of description and discussion to keep the system uncomplicated enough to operate in the harshness of real-world field work of aiding minority groups rehabilitate their homes.

Cette communication présente un procédé pour évaluer la performance de logements qui existent et pour projeter des changements appropriés pour les usagers qui désirent améliorer cette performance. Le procédé a été élaboré à la suite de travaux pratiques ayant pour but d'aider des familles apparenant à un groupe minoritaire à évaluer leurs logements. Le procédé est conçu pour permettre à un groupe d'experts en logement d'aider des familles à satisfaire leurs besoins individuels d'usagers. Tenant compte du logement d'une famille et des priorités qu'elle se donne pour son amélioration, des revenus, du financement disponible, le procédé amène des choix réalistes de rénovation possible. Les sujets discutés comprennent les problèmes de l'interface entre le "technique" et l'"humain" qui se posent à l'usager, la présentation de l'information, l'analyse des exigences de logement, l'analyse de l'échelle de valeurs de l'usager de logements individuels, l'analyse financière de l'usager et l'organisation du service conseil. Ce mémoire se maintient à un niveau modéré de description et de discussion dans l'intention de garder le système assez simple pour qu'il dans la rude réalité de la pratique de l'aide aux groupes minoritaires pour l'amélioration de leurs logements.

Key words: Analysis; cost; evaluation financing; housing; improvements; individual; inspection; minority groups; performance; real world; rehabilitation; synthesis; system; user needs; user values.

Project Introduction

This paper presents a process for evaluating performance of existing homes and planning suitable changes for users who would like to improve this performance. The process was developed through work with the Community Advocacy Depot and families from the North Champaign-Urbana black community in the summer of 1970. This process consists of inspecting the home and helping a family select the changes most beneficial for its needs, determining how much money a homeowner will have available to spend, and helping a homeowner decide which changes to make with his limited money.

A group or agency with information and access to financial aid sources, and with experience and knowledge of improvement techniques can be the catalyst which sets the delayed process of repairs and changes into motion. The steps presented here provide a vehicle through which to offer such help. This procedure does not result in an analysis of the economic desirability of improvements over other alternatives for a home, because very often the only other feasible alternative is to do nothing. Rather, the process gives an anlysis of the economic possibility of completing the most desirable improvements with the available money, i.e., the possibility of maximizing performance of the house within the ranges of realistic choices available.

Project Goals

The initial objective was to satisfy the need for information and for methods to accomplish home improvements. Homeowners requested aid in evaluating and repairing their homes. They needed to know the conditions and availability of funds through government programs, the specific parts of their home to consider, and a way to choose the most important improvements.

A second objective was to create a standard process the Community Advocacy Depot could use to aid any family requesting help in improving its home. Merely updating the data on funding and costs could keep a simple procedure current, as well as relevant and effective. At the same time, the continual use of one method could gradually educate neighborhood homeowners to use the procedures themselves either for routine care of their own homes, or to aid other homeowners making repairs. The procedures presented here were intended to work toward this final end of self-sustaining neighborhood maintainance.

Project Environment

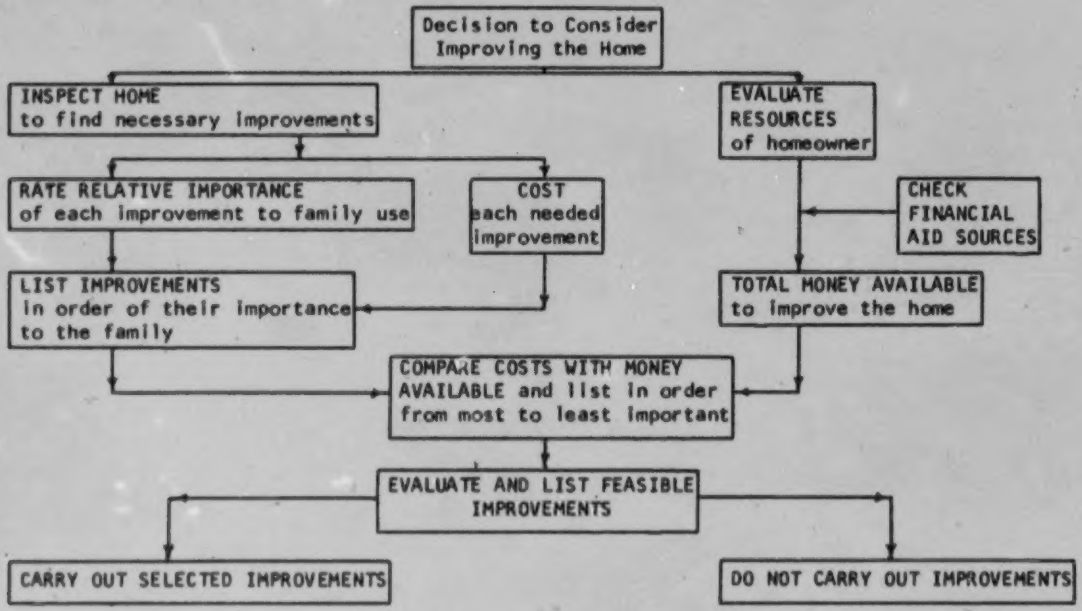
Champaign-Urbana, a university community of about 150,000 suffers a chronic housing shortage. The growing demand of students for housing has maintained a vacancy rate of less than 1% in the city. Thus rents, and housing costs in general remain very high.

These factors influenced many black residents to buy older homes in North Champaign-Urbana even on the somewhat unfavorable contract terms offered to them. While the basic structure of most of these older homes remains sound, family growth and deferred maintenance have aggravated the minor repairs the home probably needed when purchased. Most of these families with housing problems now consider repairing their homes because of a lack of money to buy a new home, a commitment to pay the balance of a contract to buy the existing home, or an inability to sell their house.

In early 1970 the Community Advocacy Depot was formed from a preceding University of Illinois advisory group which various black community groups had requested to aid them in attacking their housing problems. CAD sought to utilize university people with engineering or architectural expertise to provide residents with the knowledge to make their own decisions on community improvement. With either volunteer or university-aided workers, CAD could offer its consulting services free of charge to any resident requesting aid. The eventual goal of the organization was to educate community residents to aid each other both in improving their present homes and in buying new homes.

The Home Improvement Process

The following flow chart summarizes steps in evaluating home improvements. An explanation below describes each step.


Decision to Consider Improving the Home
INSPECT HOME to find necessary improvements
EVALUATE RESOURCES of homeowner
RATE RELATIVE IMPORTANCE of each improvement to family use
COST each needed improvement
CHECK FINANCIAL AID SOURCES
LIST IMPROVEMENTS in order of their importance to the family
TOTAL MONEY AVAILABLE to improve the home
COMPARE COSTS WITH MONEY AVAILABLE and list in order from most to least important
EVALUATE AND LIST FEASIBLE IMPROVEMENTS
CARRY OUT SELECTED IMPROVEMENTS
DO NOT CARRY OUT IMPROVEMENTS

Inspect Home

The Inspection Matrix of figure 1 organizes information given by the initial inspection on the home's condition. This matrix acts as a check list for inspecting a house, room-by-room. 0, 1, or 2 ratings describe the performance of each physical component of each room; showing satisfactory, partially satisfactory, or nonsatisfactory performance, respectively.

The room-by-room divisions of the matrix correspond to family thinking concerning its home's performance and function. For example, a dining room might seem overcrowded with furniture and activities while the living room adjacent to it was saved only for special occasions in the family's living pattern. Families seem to consider each room an individual unit. Listing the physical parts of each room on the vertical axis of the matrix helps assure a complete check of the home, thus minimizing repeated visits for appraisal of the home. Division by building physical subsystems also may provide a basis for clear comparison to government property rehabilitation standards, housing codes, or FHA minimum standards. For example, roofs should keep out water and have some controlled method of drainage; access through a bathroom cannot give sole entrance to a habitable room, basement, or hallway. If a family uses certain funding programs e.g., Urban Renewal, Section 235, these set criteria which must be used to judge the home. Otherwise, only the family's own judgement of its needs in the home, along with some basic performance requirements, govern home inspection.

Inspection should also give at least a rough estimate of the remaining useful life of the home. This need not be more definite than to recognize whether a home will degenerate beyond repair within five to ten years, or whether improvements could extend the useful life to fifteen to twenty years. This estimated life will give the homeowner an idea of the maximum time span over which to plan home investments. This life span should be checked against the time frame of planned changes in the neighborhood such as Urban Renewal which might adjust the house life.

The Dollhouse Model

In discussion with homeowners it became apparent that when they attempted to plan extensive changes to their homes they often found it difficult to visualize changes and decide on sets of different alterations. Blueprints seemed confusing to homeowners inexperienced in construction. A small dollhouse model of a home with parts which one can move into various layouts and arrangements was developed to aid these homeowners.

The dollhouse consists of interior and exterior walls, windows, doors, and pieces of furniture, all of which a user can rearrange. This model attempts to divide a home into modular components so that some few basic modules may represent many different types and layouts of homes.

Cardboard modular panels represent walls, and a soft board provides the base on which to build the model home. Panels representing exterior walls have one white face and one black face; while panels representing interior walls have two white faces. Balsa wood furniture aids model users in visualizing the space they arrange more realistically. All windows and doors are drawn on paper and cut according to the size of each unit. Rubber cement can attach them to the panels in any way a homeowner wishes to place them. The rubber cement enables a user to peel the cutouts off the panels and move the cutouts to another location. A scale of 1/8" = 1'0" makes the model compact and easy to carry.

With a real physical model of their home, a family could better visualize and illustrate to builders their ideas for improvements. Also, the family would more likely develop additional, more livable changes if they could experiment on this model house and physically see some results.

Rating Process

A family must decide which possible improvements to its home would most benefit the home's performance, i.e. which to make first with a given amount of money.

In earlier field work, families attempted to give a one to ten rating to each room. This rating measured the importance of the number of activities taking place in the room and the relative importance to family living patterns and home performance. This rating was then used to scale ratings of all improvements to that room noted in the inspection matrix. This method proved too confusing to the housing users, and complicated in information transformation. A one to ten scale seemed too finely divided for a family to decide on a definite rating. Also, the idea of trying to fix the importance of each room seemed much less beneficial than rating the importance of individual improvements themselves.

The goal of the matrix is to clearly state the desired alterations and have the family place its own rating on each desired alteration. Once the matrix shows all needed improvements by rooms, a homeowner can begin to organize these into more meaningful lists.

As a first step in the rating process a homeowner should pick out "vital" improvements from the matrix. These essential repairs could be derived in two ways.

First, financing programs might dictate house performance standards which a home must meet. For example, homes improved with urban renewal funds must meet Property Rehabilitation Standards set by each local authority. Before closing an FHA mortgage, FHA must inspect a home to certify that it meets FHA minimum property standards. Improvements which are necessary to obtain the desired financing program and local codes must be rated as vital. Also items should be designated as vital if they could lead to extensive damage in the future if not corrected soon. Improvements will also become "vital" from the opinion of a home's occupants if they consider a certain group of changes essential or highly desirable to the family activities. The rating requires decisions by the family themselves to segregate these vital improvements from less urgent improvements.

The designation of "vital" should be applied as an overwritten rating on any such 1 or 2 ratings appearing in the original survey and all such repairs should then be listed in the Vital List.

A homeowner should group remaining improvements (nonvital) listed by rooms into functional lists under the categories of (a) Living-Eating-Food Preparation (b) Sleep-clothes-Storage (c) Exterior and (d) Bath-Utilities. Such lists should have 2-rated repairs first, then 1-rated repairs. Consolidating improvements by room into improvements by general classes of activity should help a family to weigh the relative importance of improving the performance of a certain part of the home. A family does this by considering the relative importance it attaches to the family activities affected by that performance. Figure 3 illustrates this consolidation of the example given in figure 2.

A family should consider each of the four nonvital lists to rewrite them with the improvements it considers most necessary closest to the top of each column. Choose the most important, next most important, etc. of the "2" rated improvements in any one list; then do the same for "1" rated improvements. Criteria for such rating can be (a) how much each would save in housing costs (b) how much each would aid family activities, (c) how many family activities each would affect. Each family can weigh these criteria one to another as it sees fit for its own needs.

With each list ordered from most to least important changes, a homeowner can finally structure one list of needed and desired changes by their importance to his family and its needs.

The process of creating the one list of all remaining improvements is carried out by looking at each row across all four lists of needed improvements, by considering the four changes at the top of each list, and choosing the most important of these four for the first in the combined list of "Needed Improvements". The decision between the four changes is made by selecting that which would give the most performance benefit against the family valued criteria (faster or similar activities, money saved, etc.). Next, exclude the chosen change from the list on which it appeared. Repeat the choice process with the four improvements now at the top of the lists and place the next choice as the second most important in the new list of "Needed Improvements". Continue this process until all improvements in the four old lists are combined into the new list.

Costing of Improvements

Both comparison shopping and estimates from contractors on their labor costs can give costs estimates for needed improvements.

The price of a change in the home depends on (a) the quality of materials used (b) the quantity of materials used and the quantity of construction labor and management necessary. It is important to remember that each improvement may require the work of more than one subtrade, and that often the cost of work such as this has its largest proportion in its "hidden" aspects, in temporary work, and "fixed" management costs.

It is highly advantageous to keep the request for costs at the individual task level in order to compare and consider as many alternative strategies as possible to minimize costs i.e. hiring various contractors, the homeowners doing varied amounts of the work themselves, using different quality materials, packaging the individual tasks into serial contracts etc. While a homeowner needs to do as many repairs as possible himself to minimize costs, he must not try to assume more extensive tasks than he can possibly accomplish. The final decision on the character and costs of each improvement must prove realistic as well as economical.

It would probably be cost advantageous in rehabilitating a number of houses to group similar tasks in each into one contract.

Improvement List

Figure 4 shows the final form of the two example lists of improvements and their costs developed from the example of figure 3.

Homeowner's Resources

A family must determine how much it can afford to spend for home improvement. Monthly income appeared to be the most common planning base for family expenses. A family may budget their resources using a form such as that given in figure 5 to itemize all monthly income and expenses.

This monthly accounting table is not essential if the family can determine by some other means an amount of money it is willing and able to invest in its home.

Its decision could be in terms of a lump sum available immediately for expenditure on repairs or monthly payments applicable to a home improvement loan for repairs. Alternately a homeowner could plan to space improvements over a period of time and allocate money to repairs as it becomes available.

The monthly amount which a family could devote to home repairs multiplied by (a) the present worth factor appropriate for the current market interest rate and the families credit rating and (b) the number of years over which a family would repay the debt gives the capital loan a family could immediately afford to borrow to finance house improvements.

Setting the time over which to capitalize this monthly payment involves a family decision on (a) the duration for which it is willing to make payments on this debt, and (b) the estimated duration made at the time of the house inspection of how long the improved house would maintain its acceptable performance level. Whichever is the shorter time period gives the maximum term of a home improvement loan and should be used in arriving at the capital sum available for improvements.

In many cases, a five year period seemed the longest time over which homeowners found repayments on a home improvement loan worthwhile. Even a remodeled older home seemed to lose a substantial part of its family estimate of value and market value in this period. Also, the probability of unforeseen family needs and income changes affect this decision. Many families hope to save money for a new or different home within this time and such savings have to be deducted from the monthly sum available for improvements.

Neighborhood conditions also change and cause changes in the property value of the individual home which in turn affects the decision on whether or not to improve the house. Such externality changes are handled as input to the appraisal of the remaining life of the house if the improvements were to be carried out.

Financial Aid

Financial aid may supplement a family's own resources. Local banks occasionally make Title I home improvement loans. The FHA-insured loans provide $5000 or less for repair of units physically attached to the structure. However, since FHA limits its interest rates to 5 1/2%, few banks still make the Title I loans. Urban Renewal programs, when funded, can provide grants to area residents with low incomes and without substantial resources. City Urban Renewal agencies can also supply loans of $14,500 or less for a maximum of twenty years. However, all Urban Renewal funds must be used only to bring the house up to stated Urban Renewal standards. Homeowners cannot finance repairs in this manner solely to improve the performance of the home. An organization seeking to aid homeowners to begin special funding programs should collect and constantly update information requirements and availability of all financing programs in a given area.

Total Money

Total money represents a complete capital sum presently available for home improvements. This includes the homeowner's final, lump-sum resources from savings, loans, present values of future monthly savings, or other sources; along with any supplementary aid from special funding sources such as Title I loans or Urban Renewal Programs.

This procedure must give the homeowner a complete understanding of the source, attached conditions, and possible repayment terms of a realistic sum of money which he can use to rehabilitate or improve his home.

Compare Costs with Money

A homeowner now compares the costs of the lists of vital and needed improvements with the total money available. The list of "Vital Improvements" has already received priorty rating. If the total sum of money available exceeds the total cost of all vital improvements, the homeowner can afford to carry out all these changes.

If the total cost of vital repairs exceeds the total money available, a homeowner could make the previously "2" rated vital improvements first, and as many of the previously "1" rated vital improvements as money allows. However, in this case a homeowner might reconsider improving his house. Such minimal repairs will probably extend the useful life of the house very little. If present resources cannot improve the house even to comply with the minimum housing code or rehabilitation standards, possible repairs will probably not improve performance enough to justify significant expenses. Available money might be better applied to the purchase or rental of a different home.

Money remaining after accounting for the cost of vital improvements can be applied to make changes from the list of "Needed Improvements". Beginning at the top of the list with the most important repairs, a homeowner can make improvements from the list until their cumulative cost, the costs of needed improvements plus the cost of vital improvements, equals the total money available. As figure 6 shows, a homeowner chooses "Needed Improvements" from the top of the list to as far down as his money allows.

While the above are capital costs and decisions are being made thereon, attention should be paid to the effect of these capital investments on the maintenance and operating costs over the future life of the house.

Once a homeowner has compared the list of improvement costs with available money to show a list of changes which he could make, he finalizes his decision on whether to actually make proposed improvements. His decision depends on the performance benefits of changes in the home versus the costs and obligations he incurs.

The counselor's function of helping a family determine the performance benefits and realistic costs of possible improvements ends with the comparison of improvements to available money. The homeowner must make the final decision to carry out changes to his home. Whether he completes proposed improvements or not, an efficient process of finding the most important changes needed and a sum of money available to make these changes provides a sound basis for decisions on home improvement.

Use of the Home Improvement Process

Because families requesting aid contact CAD as individuals at sporadic intervals, this process preserves the view of each family as a separate housing user and its own decision maker in maximizing the performance of its own house. While families can look at more or less standard designs for new homes which they either could or could not afford; each family and its needs and the plans and conditions of its existing house present a unique set of circumstances. To maximize the performance of each unique set (i.e. that house for that family) the above decision making process was created.

Generally families seemed to prefer knowing one CAD member who has major responsibility for working with that specific family and home. This one person assisted the family as much as possible by helping inspect the home, providing information on funding programs, helping compare material prices, etc. This one CAD member also had the responsibility of contacting other CAD members whose special technological skills or knowledge a family needs in appraising their house and the proposed individual repairs.

Alternately the family could work with a counselor who understood the home improvement process and merely contacted more experienced group members as expert help or information became necessary.

The first families to get in touch with such a service organization would probably directly contact a member of the experienced or professional group. However, as knowledge and acceptance of the group grew in the community, the "counselor" position could develop into a valuable method of educating community residents to help their neighbors make home improvements by converting the organization into an almost completely community-staffed group. This meets the eventual goal of true neighborhood self-help. However, since very personal family information would be in the hands of close neighbors, a situation which might not be acceptable to the recipients of help, some families might still prefer outside professional help.

Inspecting the home and evaluating its remaining life, rating the importance of improvements, and setting costs proved valuable methods of meeting a family and gaining its trust. After discussing and helping a family reach conclusions on its home, a counselor is in a much better position to ask delicate questions about income, cash resources, or any other information needed to locate money for improvements. In asking such personal questions, a counselor from the neighborhood itself or from a similar ethnic origin sometimes has a great advantage over an outsider.

Conclusion

This paper describes a simple and direct process for evaluating home improvement needs, costing repairs, and determining which of the most important improvements a homeowner can afford to make. Probably the ideal group to use these procedures would consist mainly of community people with the knowledge and experience to help their neighbors or contact professional help if necessary. However, from in-the-field research the actual success of any group attempting a substantial program in a low income neighborhood requires some other conditions.

Some type of funding or aid must be available for both individual families and for the agency's own interim financing. At one time Title I loans could help many individual families. Many groups have tried to utilize FHA reservations in such programs as Section 235, or Section 221(d), to help individual homeowners. Regardless of which program proves useful, the funds must be available and committed to specific families. If low-income families could have maintained their homes with their own resources, it is probable that they would already have done so.

Far fewer sources of interim financing exist compared to sources of financing for individual families. An agency will probably have to pay market interest at a bank unless it can find some special sponsor. Some aid groups have also used a revolving fund maintained by minimum consulting fees for this purpose. Any group of professional experts must find substantial financial backing to become involved in home renovation.

Finally, an organization must become known and accepted in the community. Unless the initial idea, or at least initial strong support for a neighborhood improvement group, comes from within the community, an outside group will have a serious disadvantage to overcome from the very start.

Community members, working with the group from its beginning, should form the nucleus around which to develop community control of neighborhood improvements. Thus, regardless of how long such an organization functions, it will have some lasting effect on the normal maintenance and repair given to homes in its community.

	ROOM		ROOM		ROOM				
Interior	Rating	Comment	Rating	Comment	Rating	Comment	Exterior	Rating	Comment
Shelter Floor							Shelter:Foundation		
Walls							Walls		
Ceiling							Roof		
Furnishing:Finishes							Finishing:House		
Furniture							Lot		
Utilities:Plumbing							Utilities:Sewer		
Electricity							Gas		
Temperature:Heating							Water		
Ventilation							Drainage		
Area							Area		
Access							Access		
Other							Other		

RATING SCALE
SATISFACTORY PERFORMANCE.............0
PARTIALLY SATISFACTORY PERFORMANCE...1
NON SATISFACTORY PERFORMANCE.........2

Fig. 1 Home Inspection Matrix

Interior	Dining Room		Kitchen		Master Bedroom	
	Rating	Comment	Rating	Comment	Rating	Comment
Shelter: floor	0		0		0	
walls	0		0		0	
ceiling	0		0		0	
Furnishing: finishes	1	repaint walls	1	needs repainting	2	needs new floor tiles
Furniture	0		2	need new cabinet	1 2	new bureau new mattress
Utilities: Plumbing	0		2	need new sink faucet	0	
Electricity	0		0		0	
Temperature: Heating	0		0		0	
Ventilation	2	need two new storm-screen window units	2	need two storm-screen units	2	need two new storm-screen units
Area	0		2	build new storage closet, move table	0	
Access	0		2 1	new lock on back door new screen door	0	
Other	0		0		0	

Exterior	Rating	Comment
Shelter: foundation	1	Repair NE Foundation corner
walls	0	
roof	1	repair roof over dining room
Finishing: house	0	
lot	0	
Utilities: sewer	0	
gas	0	
water	0	
Drainage	2	extend drain pipes; grade land next to found.
Area	0	
Access	2 2	new front door new lock on front door
Other	0	

Fig. 2 Example Home Inspection Results

Fig. 3 Functional Lists of Improvements

MATRIX	Dining Room	Kitchen	Master BR	Exterior
Shelter:				1 repair cor. of foun. *1 Repair roof over DR
Furnishing:	1 Repaint walls, ceiling	1 Repaint walls 2 New cabinets *2 New sink, faucets	2 New floortile 1 New bureau 2 New mattress	
Utilities: Temperature	2 Two storm screens	2 New storm-screens	2 New storm-screens	*2 Extend drain pipes *2 Grade land
Area:		2 Build storage closet		
Access:		*2 New lock on back door *1 New back screen door		*2 New front door *2 New lock on front door

FUNCTIONAL LISTS

Vital Improvements*	Needed Improvements			
	Living-Eating Food Prep.	Sleep-Clothes Stor.	Exterior	Bath-Util.
new sink and faucets, new lock on back door, extend drain pipes, grade land, new front door, new lock on front door, new screen door on back entrance, repair roof over DR	storm-screen in kitchen, new cabinets stormscreen in DR, storage closet in kit. repaint kit. walls, repaint DR,	new floor tile, new mattress, new storm-screens, new bureau	repair NE corner of foun.	-

Fig. 4 Example of Final Lists of Improvements and Costs

Vital Improvements	Cost
1. New Sink and faucet	$ 70.
2. New lock on front door	15.
3. New front door	30.
4. New lock on back door	10.
5. Extend drainpipes	20.
6. Grade land next to foundation	100.
7. New screen door on back entrance	15.
8. Repair Roof over dr	50.

Needed Improvements	Cost
1. New storm and screen units in dining room	$ 30.
2. New kitchen cabinets	100.
3. New storm and screen units for master BR	30.
4. New storage closet for Kit.	50.
5. Screens for kitchen windows	30.
6. Floor tile for master BR	50.
7. New mattress for master BR	50.
8. Paint walls and ceiling in dining room	60.
9. Plaster crack in NE foundation	25.
10. Repaint kitchen	50.
11. New bureau for master BR	25.

Fig. 5 Income and Expenses per Month

Income	Expenses and Obligations	
husband's take-home pay_________	Housing	
	home payment or rent	______
	insurance premium	______
wife's take home pay (if steadily employed)_________	taxes	______
	estimate for maintenance and repairs	______
other income______	estimate for utilities	
	electricity	______
	gas	______
	water	______
	Living Expenses	
	food	______
	clothing	______
	insurance premiums	______
	education	______
	medical and dental	______
	car (operation, repairs)	______
	other transportation	______
	recreation	______
	emergencies	______
	miscellaneous (dues, contributions, etc.)	______
	Fixed Obligations	
	installment payments	______
	other debt payments	______
	state income tax	______
	retirement fund	______
	savings	______
	miscellaneous	______
Total Income______________	Total Expenses	______

Total income less total expenses shows the money a family can set aside each month to eventually or immediately improve their home.

Fig. 6 Comparing Available Money with Costs--Total Money Equals $500

Vital Improvements	Cost	Needed Improvements	Individual Cost	Cumulative Cost
New sink and faucet	$ 70.	New storm and screen units in dining room	$ 30.	$340.
New lock on front door	15.	New kitchen cabinets	100.	440.
New front door	30.	New storm and screen units for master BR	30.	470.
New lock on back door	10.	Screens and storm units for kitchen windows	30.	500.
Repair roof over dining room	50.			
Extend drainpipes	20.			
Grade land next to foundation	100.			
New screen door on back entrance	15.			

Performance Specifications for Office Space Interiors

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The Public Buildings Service of the General Services Administration, which creates a $200 million annual market for Federal office buildings, commissioned the Building Systems Section of the Building Research Division of the Institute for Applied Technology, National Bureau of Standards, to conduct an experiment demonstrating the feasibility of the Systems Approach to designing, specifying and constructing complex buildings. Thus, the Government is using its building program for its own benefit while making a public experiment intended to replace prescriptive specifications with Performance Specifications based upon a specific definition of user's needs. This approach will modify-- perhaps drastically in some instances--the products, rules, people, resources and energy involved in the building process. It is not intended to supplant the traditional design process or construction process, but rather, it is intended to combine all the elements in the design and construction process to more precisely and efficiently produce a desired result. The principles of this project are examined in such terms that their application to other projects may be expedited.

Le Service des Bâtiments Publics de l'Administration des Services Généraux qui crée un marché annuel de 200 millions de dollars pour les bâtiments de bureaux fédéraux a chargé la Section des Systèmes de Construction de la Division de Recherches sur la Construction de l'Institut de Technologie Appliquée, Bureau National de Standards, de procéder à une expérience démontrant la possibilité d'appliquer la méthode de systèmes au dessin, à la spécification et à la construction de bâtiments complexes. Ainsi, le Gouvernement utilise son programme de construction pour son propre bénéfice tout en faisant une expérience publique qui a l'intention de remplacer des spécifications consacrées par l'usage par des spécifications de performance fondées sur une définition spécifique des besoins de l'usager. Cette méthode modifiera - gravement, peut-être, dans certains cas - les produits, règlements, personnel, ressources et énergie impliqués dans le processus de construction. L'intention n'est pas de supplanter les procédés traditionnels de planification ou de construction, mais plutôt de combiner tous les éléments dans le processus d'ébauche et de construction pour obtenir le résultat désiré plus précisément et de façon plus efficace. Les principes de ce projet sont examinés sous différentes rubriques de façon que leur application puisse expédier d'autres projets.

Key words: Building Process; Building Systems; "Closed" Systems; Management; "Open" Systems; Office Buildings; Performance Specifications.

The PBS Performance Specification for Office Buildings is a "real-world" experiment to demonstrate to all participants in the present building process the usefulness of the Systems Approach and the Performance Concept to specifying, designing and constructing complex buildings and that such a new approach will yield improved facilities without increased costs in less time than present construction. It assumes these benefits can only come from changes in the traditional building process. The Federal Government has chosen to use its building program for its own ends while making a public experiment to improve that program.

Project Goals

One implication of a Government experiment is the idea that the methods used to achieve goals must be transferable to and reproducible in the public sector. The goals of this experiment are any, and hopefully all of the following as compared to traditionally designed and constructed buildings:

- Increased quality--the buildings procurred must be more responsive in some measurable way to the needs of the users,
- Decreased cost--the buildings and building operations must achieve a reduction in first cost and operating costs, and
- Improved management techniques--the changes in the building process must result in greater efficiency.

These goals may be achieved in the procurement of specific Federal office buildings, by means of a Performance Specification. This project is sponsored by the General Services Administration/Public Building Service (PBS) and prepared by the Building Systems Section of the Building Research Division of the Institute for Applied Technology, National Bureau of Standards.

How PBS Builds Today

PBS is the agency responsible for the construction of Federal office buildings for use by tenant Federal agencies. In the conventional procedure, PBS determines from its program plan the need for Federal agency office space. When a specific project is approved and funded, a site is secured and an architect is retained to execute a program and design and construction drawings responsive to requirements stated by PBS. After approval of drawings and receipt of funding for construction, the drawings and specifications are bid. Subsequent stages are construction and occupancy. The entire process takes from five to seven years.

This is the typical approach to Federal construction, much of state and municipal construction, and a large share of private institutional construction. These agencies are program builders. They have a continuous program of construction. Program builders have common methods and problems. Some problems are:

- Our present building process has few satisfactory methods for assuring that users are satisfied with a building's performance, and actually users are normally not included in the decision making which determines their physical environment;
- Normal specification methods, while convenient, also often preclude innovation, raise costs, and discourage impartiality of product selection;
- Existing contracting procedures don't fully benefit from building process improvements generated by the manufacturing and construction elements of the industry;
- Goals are often unclear, and data about product performance levels aren't explicit, thus the ability to evaluate objectively is hampered and the transfer of evaluative information is difficult; and
- Program builders tend to improve procedures gradually due to the project-by-project nature of their procurement and therefore slow improvement is inherent in this fragmented building process.

Any innovation in the building process must address itself to these problems and must develop ways to accommodate change in building and building management. The following describes one such approach.

New Ways to Build

It was because of these problems that a Presidential Task Force determined the Federal Government should use its purchasing power in its own interest by means of a Program for Performance Based Federal Procurement. Mr. John P. Eberhard was largely responsible for developing that rationale. He stated that "in modifying Federal purchasing practices for the purpose of this program, primary emphasis should be placed on formulating performance criteria (rather than product specifications) for the products, systems, and services purchased. The following arguments can be advanced in support of this recommendation:

- in doing so, it frees industry to innovate, limited only by the requirement that it perform certain specified functions,

- it encourages cost reduction for itself, and cost reduction in industrial production, awarding contracts to the lowest bidder under these conditions,

- it serves as a pilot customer for technical innovations in many areas where it represents a large enough percentage of the total market or a big enough bulk purchase. . .to make it attractive to industry,

- it serves as an occasion for the development of performance criteria--which can then become the basis for industrial standards--furthering the development of performance-based standards--in itself a stimulus to innovation in industry, and

- the use of performance requirements derived from the needs of the actual users of buildings helps to ensure that buildings will be more responsive to the users' needs."

With these points in mind, PBS agreed to sponsor this research which is directed toward the application of the Performance Concept to a set of project buildings. Three conditions were defined:

- the determination of the performance required of some large portions of buildings, presented in the form of a Performance Specification,

- the complete elaboration of the technical, legal and managerial procedures (building process) necessary to accomplish procurement, and

- the allocation by PBS of a market of sufficient size to attract industry.

In this context the Systems Approach and the Performance Concept are being used in this applied research.

The Systems Approach

The most striking technological advances, are made visible by their physical machinery, their hardware. Some of these products owe their genesis to a non-physical "intellectual technology"--the application of the new intellectual techniques of systems analysis, simulation and operations research to problem solving--the Systems Approach.

The Systems Approach was successfully utilized for problem solving in military and space projects. It is applicable to building problems. They too are complex and require a multi-disciplinary approach involving the organization of many technologies. The Systems Approach has two main features:

- Goals are clearly stated in performance rather than the prescriptive terms of particular technologies with the advantage that performance terms force decision makers to make comparisons of alternative solutions, and

- It emphasizes inter-relationships within a system where the traditional approach divides a problem into manageable sub-problems, thereby losing those factors which are relationship-based or dynamic.

The comprehensive view of the Systems Approach enables us to trace the effects of any set of decisions upon all other relevant decisions. A system is defined as any collection of men, machines, materials, energy and rules which interact to produce a desired effect.

In applying the Systems Approach (fig. 1) to building problems, several steps must be followed:

- PROBLEM DEFINITION--the quantitative and qualitative statement of the disparities between the actual state of affairs and what is desired or ideal,
- GOALS--the statement of what is necessary to reduce or eliminate the disparities enumerated in the Problem Definition,
- ANALYSIS--the generation of the greatest possible amount of data about the Problem, Goals, Evaluation Criteria and Modeling, and the quantitative and qualitative aspects of their elements and relationships,
- SYNTHESIS--the development of alternative solutions for achieving the Goals,
- MODELING--the simulation of the performance of the alternative solutions before the Evaluation Criteria are applied and one solution is selected,
- EVALUATION CRITERIA--the quantification and qualification of the Goals statements in detail and priority for the purpose of measuring the effectiveness of a solution in the Models,
- SELECTION--the determination of the solution which in the Models most nearly meets the Evaluation Criteria,
- IMPLEMENTATION--the execution of the selected solution in the real-word,
- USE--the placing into effect of the Implemented solution and its operation, maintenance, repair and improvement over time, and
- FEEDBACK--the flow of information from any step in the process to any other step for the purpose of validation so that better decisions can be made in each stage in this and following building cycles.

Many of these steps are made in the conventional design and procurement process, but those left out are critical--Modeling, Evaluation Criteria, and Feedback. Limited aspects of these three steps appear in the traditional process but without the rigor of the Systems Approach they are relatively ineffective.

Just as these steps supplement the traditional approach, so do they increase the effectiveness of the iteration that is a part of any solution seeking process. More effective Modeling and Evaluation Criteria applied to the alternative solutions generated in any phase of the process provides effective Feedback from one phase to the next, thus aiding in the development of a more precise Goal and the Selection of a more effective solution.

The Systems Approach doesn't supplant the traditional process, but rather amplifies and gives it more assurance of success. Especially important is the formalization of Feedback before Implementation into Models for pre-testing of alternative solutions and validation Feedback beginning with Implementation and continuing throughout Use. The Systems Approach is an idea, a method--a more rational way of looking at problems.

The Performance Concept

The Performance Concept is an integral part of the Systems Approach. It provides an organized procedure by which it is possible to state the desired attributes of anything without regard to the specific means to be employed in achieving a solution. These desired attributes are independent of particular materials, devices, or systems, and may be derived from the following questions:

- Who is the user?
- What are the users needs?
- Where do the needs exist?
- When and for how long do the needs exist?

In order to describe these needs, Performance Requirements must be developed. These will take the form of declarative statements.

In order to quantify those statements, Performance Criteria must be developed. These contain a measure or a range of measures of the needs and involve, in most cases, a numerical statement of the Requirement.

In order to know whether or not the Criteria will be met in the solution, performance evaluation techniques or Tests must be developed. These may be physical tests, simulation, or the judgment of experts.

Combining Performance Requirements, Criteria, and Tests for any given System constitute a Performance Specification for that system.[2]

Technological Innovation and the Performance Concept

The Goal of the Performance Concept is the assurance of desired performance delivered to building users. The project Goal is not necessarily to develop innovative building elements, although this is a possible response to the Performance Specification. All solutions satisfying the Performance Specifications are acceptable.

Innovation, however, is associated with the Systems Approach and the Performance Concept in practice. Stating performance required, rather than specific materials or designs, enlarges the possible range of solutions and stimulates innovation. By developing requirements for large portions of a building (the System), functional integration is permitted and tradeoffs between System parts (subsystems) can occur. Many manufacturers feel that Performance Specifications place their research and development capability in closer contact with users than is presently possible, thereby making their investments more relevant and sensitive to the marketplace.

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[2] PBS Building Systems Project Status Report, an unpublished NBS report, 1967.

If the explicit market of a particular project is of a sufficient size, the expenses of innovation may be justified by that project alone. If the size of an explicit market is small, industry may look beyond the project to make its own assessment of commercial feasibility. The PBS project utilizes this latter idea, the implicit market.

Innovations are also possible in the procedural areas of the building process. New methods of financing and management may be appropriate.

Innovations, then, occur in many areas within the Systems Approach and Performance Concept, and are stimulated to occur when the performance specified is not achieved in traditional ways or with traditional products.

The major practical application of the Performance Concept in the building industry at this time is the development and use of Performance Specifications in the procurement of buildings. In the United States and Canada there are six performance-based procurement projects at various stages of development in addition to the PBS project.[3] All the projects have a basic procedure that organizes a "market" large enough to motivate industry research and development capability to make innovative responses to Performance Specifications, or to combine existing elements in new ways. Obviously, innovation is not necessary where the Specifications can be met in other ways.

None of these projects attempts to specify entire buildings. Those building parts comprising the more repetitive, less unique conditions are specified and referred to as the "System". The unspecified portions are "Out-of-System" and are procured conventionally.

The broadest use of the Performance Concept is as Performance Standards and Performance Codes. If the evaluative techniques are reproducible, and the Requirements are reasonably common, a duly constituted body may legally adopt and enforce the use of the Specifications as a Performance Code or Standard, or they may become a de facto Standard through usage.

The PBS Research Project

The project researchers structured the work into two sequential phases. They analyzed the procedures of PBS for providing office buildings. The outputs of the analysis are the Working Parameters listed below. These provided the basis for many decisions affecting the Specification. Secondly, they synthesized alternative means for providing buildings. The output of the synthesis effort is Volumes I and II, The PBS Performance Specification for Office Buildings. A discussion of this follows the discussion of the working parameters.

Working Parameters

The working parameters developed during the analysis phases were:

- Office Building Schematic Organization,
- Gross Utilization and Building Configuration,
- Tenant Profile, and
- Criteria for Defining Project Scope.

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[3] School Construction Systems Development (SCSD), University Residential Building System (URBS), Schoolhouse Systems Project (SSP), Academic Building System (ABS), Recherches en Amenagements Scolaires (RAS) and Study of Educational Facilities (SEF).

Office Building Schematic Organization

An analysis of Federal Office Buildings showed that their elements can be classified by vertical location and function.

Elements by vertical location are:

- roof, including penthouses and towers,
- typical floors,
- special floors, including auditoria, court rooms, equipment rooms, etc.,
- ground floor, and
- below grade floors.

This project describes subsystems for typical floors, partitions (space dividers) and all structure above the foundations. It also describes the relationship between all the subsystems (the System) and the other parts (Out-of-System) of the project buildings.

Elements by function are:

- exterior wall including structural elements,
- core, including stairs, elevators, toilet rooms, electrical and telephone closets, machine rooms, elevator lobbies, shafts, etc.,
- core corridor,
- special rooms including courts, cafeteria, mechanical rooms, auditoria, parking, etc., and
- typical office space including offices, public and private corridors, reception spaces, etc.

This research concerns typical office space and the core corridor. It also involves the supporting structure of the whole building above the foundation.

Gross Utilization and Building Configuration

The total area of typical office floors, not containing special rooms was analyzed by function into the following approximate percentages:

• Exterior wall	3%		100%
• Core	10% to 8%	17%	
• Core corridor	7% to 9%		
• Typical office space	80%		

The Gross Utilization (G.U.) factor is defined as that percentage of total floor area forming typical office space. An NBS analysis showed that an office building composed mainly of typical floors having a G.U. factor of 80% will have a total building area utilization of 70%.

An NBS analysis of PBS buildings also showed that a high G.U. is only achievable when the length to width ratio of typical floors is between 1:1 and 1:2.

Furthermore, as typical floor area decreases to less than 20,000 sq. ft., a G.U. factor of 80% is difficult to achieve since core service elements do not decrease proportionately. Similarly, typical floors over 30,000 sq. ft. in area require double cores which adversely affect the G.U.

Tenant Profile

An NBS analysis of the organization of occupants of typical office space showed that users are members of each of the following three classifications:

- Tenant--an organizational unit that operates independently. (Examples - 500 man office of Internal Revenue, 1 man office of Bond Sales),
- Address--an area from which direct access to a public corridor is provided; the tenant is composed of one or more addresses, and
- Space--an area defined by partitions, and forming the physical habitat of the worker/user; the address is composed of one or more spaces.

An NBS comparison of Gross Utilization and Tenant Profile found that approximately 95% of all PBS tenants could be accommodated on a single 20,000 sq. ft. floor, thus justifying the establishment of this lower area limit.

The Tenant Profile can establish the "mix" of offices accommodated on typical floors. This can be used to develop a range of sizes for typical floors.

Criteria for Defining Project Scope

Four factors were considered in making the selection among the elements classified by location and function for inclusion in the Specification:

- quantity of System Built Elements measured as a percentage of the building construction cost,
- importance of various building aspects to the user,
- potential for improved performance, in terms of costs and benefits, and
- adaptability for use over a wide range of geographic and climatic conditions.

Of these elements, only the typical floor space is an obvious selection. It was selected through an examination of all four factors. A Federal Office Worker Questionnaire was used to determine their degree of influence on the user.

The typical office space consists of an exterior enclosure subsystem, an interior partition subsystem, and the ceiling to floor assembly or

Floor-Ceiling Sandwich (FCS). The interior partition subsystem, with its impact on the user and its clearly defined interfaces, makes a good selection, but it hasn't adequate market quantity. The Floor-Ceiling Sandwich includes a complex of services which represent approximately 36% of the basic construction cost. It is a more complex, and significant selection. These two together have an important impact on the user and represent a large portion of building costs. They were selected for the Specification. The exterior enclosure subsystem is affected by unique climatic conditions and architectural design considerations. It was therefore not selected.

In addition to the interior partition subsystem and the Floor-Ceiling Sandwich, it was decided to include the total building structural subsystem in the Specification. This was done because of the difficulty of isolating the structure in the Floor-Ceiling Sandwich from the rest of the structural subsystem.

The Matrix--The Basis for the Performance Specification

Having determined the scope of the Specification, a method was developed to consider the user with respect to the building, so that his needs would help to generate the Specification. The method is a Matrix relating Attributes to Built Elements (fig. 2). Built Elements (materials and products) contain or provide Attributes (qualities and characteristics) and a Matrix was developed to show these relationships. Each Intercept in the Matrix contains information in three forms:

- Requirement--the qualitative statement of the desired performance,
- Criteria--a quantification of that desired performance, and
- Test--the evaluative techniques assuring conformance with the Criteria.

Since the Matrix interacts Attributes with Built Elements, it is a Model of the office space in-use. The Matrix can be expanded to include the design and construction decisions which depend on conditions and constraints in the building process.

Volume II of the Specification as is explained in the following paragraphs includes information in that part of the Matrix, labeled "Building in Use." Decisions in the part of the Matrix, entitled "The Process," will be made by manufacturers in proposing specific Built Elements in response to Volume I of the Specification.

In generating Requirement and Criteria statements about Attributes, research must be done in the part of the Matrix, labeled "The User." These Attributes, directly affect the office worker. They derive from his support Requirements--Life Support, Task Support (man and machine), and Psychological Support, each of which demands a range of Environmental Attributes to accommodate and benefit the user. To develop this information requires extensive research which was outside the scope of this project.

From these support Requirements an office building may be described as an information processing system, composed of the building, people, rules, and energy for operation. An NBS analysis based on PBS data showed that the life cost of such a system over 40 years is approximately:

- 92% cost of people processing information (salaries),

- 6% building maintenance and operation, and
- 2% first cost of the building.

It is evident that building first-cost reductions can have only limited benefits. First cost, and maintenance and operation costs, together are more significant. While Government procedures preclude explicit trade-offs between them, performance levels can be established which reflect life cycle cost considerations. A more thorough analysis of users' needs, however, will ultimately prove more beneficial.

Derivation of the Performance Specification

The Matrix constitutes an information storage and display mechanism for developing the Specification. It is also a check list to ensure comprehensiveness.

All the Requirements, Criteria and Tests developed with the Matrix are presented in the Specification. The information was developed by architects, electrical, mechanical and structural engineers, space-planners, test-development engineers, fire safety engineers and acoustic and durability specialists. Representatives of various sectors of the building industry as well as the management and specialists of PBS were consulted throughout the projects' development. Their comments and ideas were fed back into the work. This liaison is simply one facet of that aspect of the Systems Approach which requires the consideration of all the participants and resources in the building process having a bearing on the development of the System.

Legal Framework for the Performance Specifications

The legal framework necessary for using the Specification for the procurement of buildings by the Government, and the nature of legally binding and implementable contracts, were investigated by PBS and NBS early in the project. It was found that the Federal procurement method of Two-Step Formal Advertising, which requires the separate submission of Technical Proposals as a first step and Bids as a second step, was applicable to the procurement of buildings. In the first step of this Two-Step procurement, System Offerors are authorized and encouraged to submit proprietary Technical Proposals with different basic approaches. Proposals are developed and evaluated solely on the basis of the Specification without any consideration of price. Proposals which after discussion and any revisions are determined to meet the performance specified are classified as "acceptable." Proposals which after discussion and revision are still not reasonably susceptible to being made acceptable are classified as "unacceptable." Upon completion of Step-One, a formal Invitation for Bids, Step-Two, will be issued only to those System Offerors whose Technical Proposals are acceptable. The Invitation for Bids requires each System Offeror to submit the price for his acceptable Technical Proposal. Bids will be by unit prices applied to bills of quantities prorated on the basis of bid equalization factors so that competitive bids may be equitably compared. The contract which may result will be awarded to the lowest bidder.

Application of the Performance Specification

Concurrent with the development of this project PBS began a review of its operations. This has been documented in a PBS report.[4] It proposes a large number of innovative procedures for building procurement. This project uses one new multi-faceted approach which involves:

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[4] Construction Contracting Systems--A Report on the systems Used by PBS and Other Organizations, March 1970.

- project management--a single, comprehensive source of decision making for design and construction,
- construction management--a professional manager for the on-site management traditionally charged to a general contractor, and
- phased construction--the non-linear design and construction of parts of a building using network analysis for planning and scheduling.

Phased construction is principally applicable to this project because the System Elements which are procured once using the Performation Specification, are installed in more than one building. The Out-of-System elements are traditionally procured and installed independently for each building. Such a complex process certainly would benefit from careful phasing.

The building process for this project which incorporates the Performance Specification and these management innovations for a multiple building procurement has its principle phases explained in the diagram, figure 3.

The Market for the Performance Specification

Information from an informal industry liaison program indicated that the office building project to which this Performance Specification is applied should have at least one million square feet of typical office space. The cost of research and tooling up for the production of System Elements may be costly, but the expected market for similar products outside this project is very large. Therefore, representatives of industry have stated they will commit resources to this project, provided clearly articulated, well-documented, user-based Performance Specifications, equally applicable to the private sector market were supplied.

Consequently, the Specification was developed with levels of performance which are in general those of commercial office buildings. The building Systems resulting from this Specification should be cost competitive with existing Built Elements but have improved performance.

Organization of the Performance Specification

The Specification is divided into two volumes, Volume I--the building process, and Volume II--the building system, the product.

Volume I contains three sections. The first is a general project overview. The second section is a detailed description of the building process. It specifies, step by step, the work necessary to plan, program, design, price, and construct buildings responsive to Volume II. This building process is described in terms of participants, activities, resources and time. The third section is the contract documents which contain only the general contract conditions and which must be appended to include such site and building data as location and size.

Volume II has basically two sections. The first covers in detail the description of the building type, what parts are in System and what parts are Out-of-System, the System and the Out-of-System relationships (interface), and relationships between sub-parts (Subsystems), the technical parameters to design, bid, test, explain and account for System quantities and to establish construction schedules, the technical parameters to evaluate the System and to compare prices *of different Systems,* and the conditions of guarantee.

The second section is the specification of the System performance in use. It has seven sub-sections, one for each of the subsystems. Each sub-section is composed of four parts which cover in great detail what comprises each sub-system and the relationship to parts Out-of-System; how the subsystem shall perform in use (in the form of Requirements, Criteria and Tests); the requirements for providing detailed technical information upon which the design, bid, tests, working drawings, and quantities have been based; and the conditions of the subsystems' guarantee.

The Relationship of Volumes I and II

There seems to be two distinct definitions of a Performance Specification in the United States. One says that a Performance Specification is a description of the desired in use performance of only the product itself. That would be just Volume II of the PBS Specification. The other definition says a Performance Specification contains not only the description of the product performance in use, but the legal and organizational conditions to plan, program, design, cost and construct the product. That would be Volumes I and II of the PBS Specification. Any definition, should consider that aspects of the building process and product performance are conditional upon each other.

In the building process, aspects of the schedule, activities, participants, law and contracts and economic resources affect and are affected by aspects of the Requirements, Criteria, and Tests, interface, Out-of-System elements and the scope of work. Examples of these conditional influences for a project procurement as is intended for the PBS Specification and was accomplished by previous systems projects will illustrate these effects. (Other examples could be made for product acceptance, such as performancce standards or performance codes.)

The more obvious examples are the relationships of Tests, Criteria and budget. The use of some Tests, such as expensive prototype Tests, is dependent on capital resources. Similarly, a Criterion level is related to the cost of achieving it. The scope of work, on the other hand, is a complex function of schedule, capital resources, and participants which affect the activities of the process. Procurement size for example, is a factor manufacturers consider in determining their participation, as is the budget. The share of the budget and the expertise of those who participate is a factor in structuring roles in the building process activities. Schedule, of course, affects Tests and Criteria. The time available to test is dependent upon the length of the schedule. The level of performance specified is subject to the time required to develop suitable products. Criteria at the state-of-the-market-art reduce product development time. Criteria beyond that state increase it. A short schedule will, therefore, control the level of performance specified; may determine the inclusion or exclusion of Requirements, and certainly affects product innovation. Similarly, some Tests are used to determine specifics of either, or both, the interface and the Out-of-System, thus delaying the procurement of the Out-of-System products until Tests are complete. These examples of the relation of product to process are not exhaustive, but they give some indication of the conditions a Performance Specification and procurement must consider.

One final and most important example concerns legal, Requirement and participant conditions. For the PBS Specification in the course of "trading-off" many management decisions, it seemed advantageous to reduce contractual relationships, to minimize interface Requirements between subsystems within the System, to unify the responsibility for the System performance and to permit certain Requirements to be written for the System as a whole. It was decided to bid the whole System rather than subsystems as the SEF project had. This determined one participant and specific activities in the building process and allowed, for example, the specification of acoustical performance for the System as a whole rather than for each subsystem. Sound is three dimensional. It would have been very difficult to translate it into Attributes for each subsystem. Few buildings are built traditionally where one contractor provides the three dimensional envelope that is necessary for acoustical control. Under traditional conditions multiple contractors provide various parts of the sound control. The acoustical performance Requirements in Volume II could not be used traditionally as they are now written. Two issues are involved here: "open" Systems versus "closed" Systems and the real needs of building users as these represent the basis for the level of performance specified. If a Performance Specification is used to more precisely fit products to the needs of users, these needs may result in performance Requirements which will require particular contractual relationships and a particular building process. The acoustic example is a condition where, if a precisely controlled acoustic environment is an important user need, the only way to accurately specify it is three dimensionally. This imposes conditions of coordination in design and construction which will affect contractual relationships and the building process. Similar examples can be made for fire safety, illumination and the thermal environment.

Open Systems and Closed Systems

The PBS Specification will result in a "closed" System. The SEF Specification for example resulted in a so called "open" System. This "open" and "closed" terminology is confusing. While SEF is an "open" System, its subsystems are "closed." The issue deals with the interchangeability of products. Even the words "System" and Subsystem" are misleading because they apply to different levels in a product hierarchy which are not comparable. This confusion may be reduced by saying that the level at which any group of products is planned to be interchangeable (open) is the level of the System. Thus anything below that level--subsystems--is not interchangeable (closed).

The SEF Specification in these terms, is a procurement of a number of Systems--Structural System, Wall System, etc.--each of which is "closed." The PBS System will contain subsystems for walls, floors, ceilings, structure, HVAC distribution, electrical distribution, and partitions. PBS is a "closed" System at a scale larger than SEF.

Such projects as SCSD, SSP (which uses an adaptation of the SCSD Specification) and URBS specified "closed" Systems at generally the same scale as that specified for PBS. The argument against this large scale approach is that interchangeable Systems will not be developed. The experience in Florida with the SSP project indicates that interchangeability will naturally occur in the market place when a large scale System is repetitively bid. The repetitive use of the SSP Specification achieved in a natural way, from industry's point of view, what was demanded of industry by the SEF Specification initially. Industry's willingness to participate in a performance procurement is essential to success. The scale of the System specified must appropriately fit the needs and philosophy of industry. The scale of the System will obviously affect contract conditions and activities in the building process.

Performance Specifications and Users Needs

Like many industries, the building industry has concerned itself with improving its production processes and products to both increase profits and expand markets. The ultimate customer, the users, should expect to benefit from an economically healthy industry and higher quality products. But generally they haven't benefited. Nor has industry greatly improved its position. Some appraisals estimate that position in many respects has deteriorated. A public policy which among other conditions regulates the availability of mortgage money and its value, controls financing particularly in public works, prescribes minimum building standards in thousands of forms, interprets the rights of labor, establishes taxation principles and rates, and controls conditions of building usage is certainly a major force in the market along with the industry and the user. These three participants--industry, the user and public policy--must be satisfied if a healthy and equitable situation is to exist. It is into this situation for the first time that a tool has been introduced which is capable of effectively manipulating the building process on behalf of its participants. It is the Systems Approach.

A tool such as the Systems Approach can improve the production process and the product for the benefit of all participants. Recognizing the needs of participants and satisfying them is essential. If this isn't done some participants may not be able to participate. If not properly done, stronger participants may dominate. Traditionally, users have been the weaker participant, not having a real voice in the decisions that determine the performance of the buildings they inhabit.

Perhaps the single most significant characteristic of the Systems Approach is its ability to incorporate the needs of all participants, particularly users. It can be used otherwise, and there is a danger it will. There are a number of reasons the Systems Approach poses this threat:

- it has been effective in reducing production costs,
- it provides a tool to take over and control the building process as a means to increase profits, and
- it has not yet provided an understanding of how people use buildings sufficient to determine increased user productivity and hence increased profits.

The Systems Approach in the building industry is in its infancy and the last reason stated is critical, because it has not been substantively developed. There is the great temptation for stronger participants to take the short term rather more easily achieved benefits, and not pursue difficult research and development on behalf of the user.

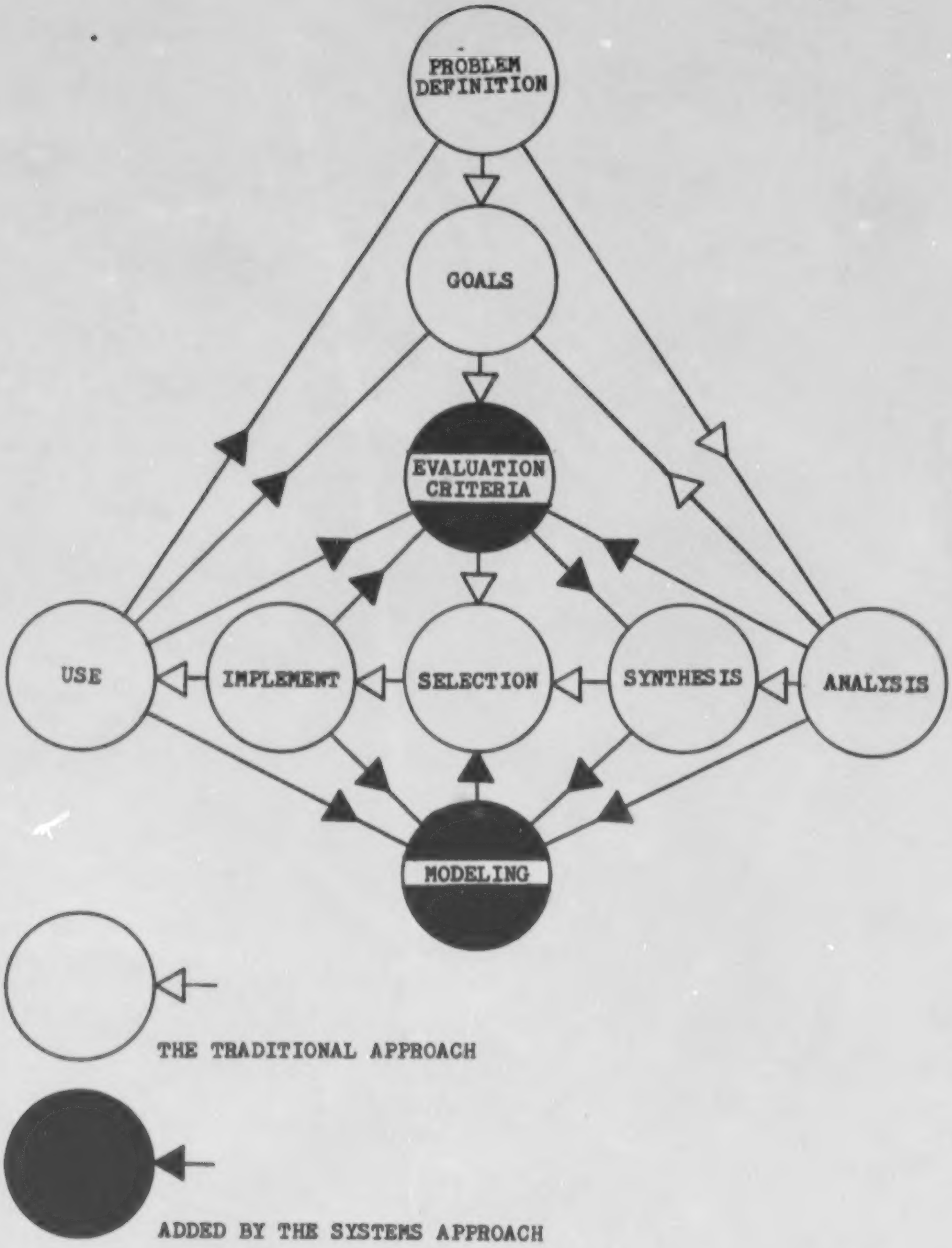
PROBLEM DEFINITION
GOALS
EVALUATION CRITERIA
USE
IMPLEMENT
SELECTION
SYNTHESIS
ANALYSIS
MODELING
THE TRADITIONAL APPROACH
ADDED BY THE SYSTEMS APPROACH

Figure 1 The Systems Approach

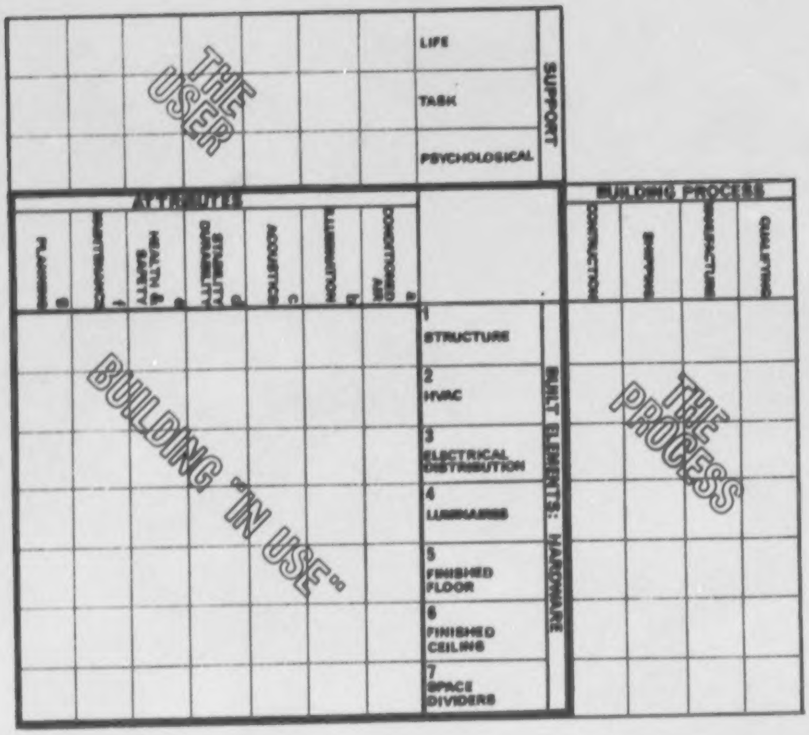
THE USER
LIFE
TASK
PSYCHOLOGICAL
SUPPORT
ATTRIBUTES
PLANNING g
f
HEALTH & SAFETY e
STABILITY DURABILITY d
ACOUSTICS c
ILLUMINATION b
CONDITIONED AIR a
BUILDING PROCESS
CONSTRUCTION
SHIPPING
MANUFACTURE
QUALIFYING
1 STRUCTURE
2 HVAC
3 ELECTRICAL DISTRIBUTION
4 LUMINAIRES
5 FINISHED FLOOR
6 FINISHED CEILING
7 SPACE DIVIDERS
BUILT ELEMENTS: HARDWARE
BUILDING "IN USE"
THE PROCESS

Figure 2 The Matrix--The Basic for the Performance Specification

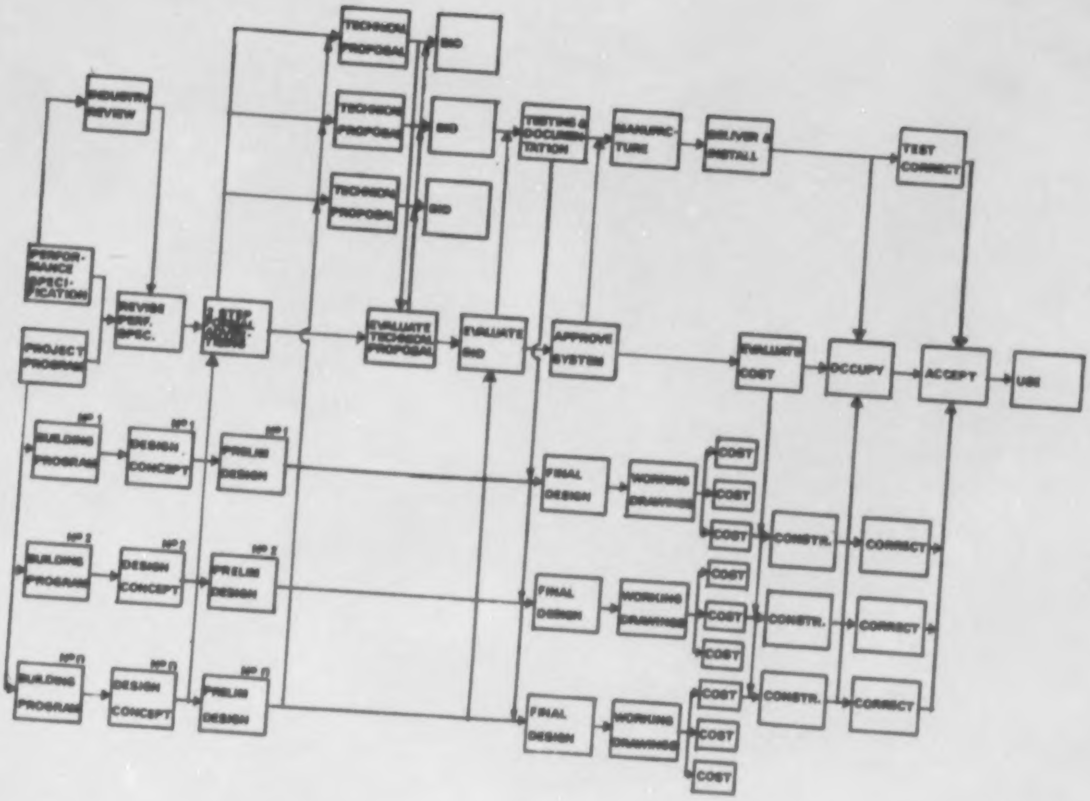
TECHNICAL PROPOSAL
BID
TECHNICAL PROPOSAL
BID
TECHNICAL PROPOSAL
BID
INDUSTRY REVIEW
TESTING & DOCUMENTATION
MANUFACTURE
DELIVER & INSTALL
TEST CORRECT
PERFORMANCE SPECIFICATION
PROJECT PROGRAM
REVISE PERF. SPEC.
2 STEP
EVALUATE TECHNICAL PROPOSAL
EVALUATE BID
APPROVE SYSTEM
EVALUATE COST
OCCUPY
ACCEPT
USE
NP 1
BUILDING PROGRAM
DESIGN CONCEPT
PRELIM DESIGN
FINAL DESIGN
WORKING DRAWINGS
COST
COST
COST
CONSTR.
CORRECT
NP 2
BUILDING PROGRAM
DESIGN CONCEPT
PRELIM DESIGN
FINAL DESIGN
WORKING DRAWINGS
COST
COST
COST
CONSTR.
CORRECT
NP n
BUILDING PROGRAM
DESIGN CONCEPT
PRELIM DESIGN
FINAL DESIGN
WORKING DRAWINGS
COST
COST
COST
CONSTR.
CORRECT

Figure 3 The Building Process for the PBS Performance Specification

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Performance Requirements for Windows

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A window is defined as any part of a vertical external wall which is predominantly filled by transparent or translucent material and where the primary function of a window is to furnish the adjacent room with sufficient daylight and provide a clear and undistorted view to the outside.
Statements of performance requirements are given under the following headings: Transparency and vision, light transmission, glare, control of solar radiation, thermal insulation and condensation, sound insulation, airing (ventilation), air-tightness, rain-tightness, strength and stiffness, control of opening light, security against illegal entry, fire resistance, escape from fire, appearance, dimensions, durability of operating parts, and durability of materials.

Une fenêtre est définie comme n'importe quelle partie d'un mur vertical extérieur, le plus souvent occupée par un matériau transparent ou translucide. La fonction primaire d'une fenêtre est de fournir suffisamment de lumière du jour à une pièce adjacente et de permettre une vue claire et non déformée de l'extérieur.

Les déclarations d'exigences de performance se répartissent sous les rubriques suivantes: transparence et vision, transmission de la lumière, éblouissement, contrôle des radiations solaires, isolation thermique et condensation, isolation acoustique, ventilation, imperméabilité à l'air, à la pluie, résistance et rigidité, contrôle de l'éclairement, sécurité contre toute intrusion illégale, tenue au feu, moyen de sauvetage en cas d'incendie, apparence, dimensions, durabilité des parties opérantes et durabilité des matériaux.

Key words: Air-tightness; performance characteristics; performance parameters; rain-tightness; sealed glazing units; wind loading; window.

1. The Term "Window"

In this context, a window is defined as any part of a vertical external wall which is predominantly filled by transparent or translucent material. The primary function of a window is to furnish the adjacent room with sufficient daylight and to provide a clear and undistorted view outside. In many cases the possibility for ventilation through the window is an important consideration.

Very often the window is made up of several subcomponents such as sash, frame, glazing, and mountings. The individual performance of each member is important when considering the whole unit. The requirements indicated in this paper are not appropriate in all cases, but most of them are, especially those for openable windows to be used in houses occupied by humans.

2. Transparency and Vision

In dwellings, clear and unobstructed vision through the windows is usually required. Therefore the glazing material should be free from waviness or other imperfections capable of causing distortion or obscuration of the view. The glazing material should have adequate hardness to prevent the formation of scratches from normal use which could distort the view.

Where clear vision is undesirable, this can be regulated by the selection of the glazing material or by other means for obscuration.

3. Light Transmission

Depending on the glazing material, some of the light will be absorbed. For ordinary window glass, about 90% of the visible light incident at right angles will be transmitted. The transmission shows a sharp decrease for light incident at an angle, while at the same time the reflection at the surface is increasing.

The light-transmitting areas of the window and the transmission factor of the glazing material should in any case be balanced to give sufficient daylight to the adjacent room.

4. Glare

Where there is a large area of glazing, the amount of light reflected from the pane surface can be of a considerable nuisance to the surroundings, and should therefore be kept as low as possible.

5. Control of Solar Radiation

In certain cases it may be preferable to reduce the transmission of light and solar heating. This can be achieved by using blinds or special heat-absorbing or heat-reflecting glazing material or by suitable shading devices.

6. Thermal Insulation and Condensation

The thermal transmittance of a window is a factor dependent on the velocity of air passing near the surfaces, the type of construction, size and distance between glazings (if more than one), and blinds and microclimatic condition. Because of its complexity it is difficult to specify any fixed value for the thermal transmittance except that generally speaking the window should give a certain thermal resistance depending on the need for insulation and comfort. Thermal bridges and moisture condensation should be avoided to prevent discomfort or damage.

Test Method

A glazed window is mounted in a test wall between a warm and cold room, where the conditions correspond to a real wall with the window installed 20-30 mm back from the outer surface and with an inner edge of about 60-70 mm. The temperature in the warm room is kept constant as near to +20°C as possible, while the temperature in the cold room is varied in 3 steps between -5°C and -25°C. Due to natural convection,the air in the warm room is slowly circulated, but the air in the cold room is mechanically circulated by means of a fan which gives an air current along the window of approx. 2 m/sec. On the outer and inner surface of the window thermocouples are glued to points on the frame, sash and glass, and these are connected to a temperature recorder.

On the basis of the measurements,a diagram is drawn which shows the temperature on the inner surface of the window under the specified conditions in the warm and the cold rooms.

In Figure 1, saturated water-vapour pressures (equivalent to each temperature measured by the thermocouples) are plotted against the air temperature in the cold room. The plot for three locations on the window is shown. On the ordinate, a relative humidity scale corresponding, at $T = 20^{\circ}C$, to the water-vapour pressure scale is also shown. The curves in Figure 1, therefore, give the limit for avoidance of condensation at the different points of measurement, as dependent on outside temperature and the inside air relative humidity at 20°C.

7. Sound Insulation

The required insulation must be chosen in connection with the local noise level and the desired indoor environmental condition. The sound transmission, however, is dependent on glazing material, number of glazings, thickness and distance between glazings. The tightness of all joints in the construction is also important in this context.

8. Airing (ventilation)

Where a window is to be the main source of ventilation in a room, the opening must be dimensioned so that the air in the room can be renewed within a reasonable period of time.

9. Air-tightness

The air-tightness of a window is determined on the basis of the air passing through the construction. The total amount of air as well as concentrated streams can cause undesirable or damaging patterns of air flow in the room. The penetration of air is dependent on the difference in air pressure on the two sides, the tightness of the construction itself and all the joints. An important factor is the lateral stiffness of the opening light which should not deflect more under windloading than that which could be taken by the weatherstripping. Hinges and locking points must be designed to exert a constant pressure on the weatherstripping.

Test Method

A glazed window of outer size 120 x 120 cm is mounted in an airtight panel where the joint between frame and panel is sealed. The air leakage will therefore be located in the window construction (joint between frame and sash, rabbet etc.).

The whole panel is fastened to the opening of an airtight chamber and pressed against a gasket fixed to the edges of the opening. Air supply to the chamber is provided by a fan.

The air is passed through a gas meter which registers the amount of air leaking out through the window at a certain superpressure against the panel inside the chamber. The leakages are measured at 10-30-50-70-60-40-20 mm of water respectively and the result is always given in m^3/h. Superpressure inside the chamber is measured by means of manometers.

The air penetration of a window versus the observed superpressure is plotted on a diagram to be compared with classification limits based upon measurements and experience for single-sash windows of size 120 x 120 cm. The classification limits are also applied to different types of windows of the same size, see Figure 2.

10. Rain-tightness

A window should be so designed that it is difficult for water to penetrate directly through the construction or into neighbouring elements. The joints between sash and frame are acted upon by driving rain and running water combined with a simultaneous wind pressure. Water can run directly through the joints or at a head of water pressure. It can be drawn into small fissures by capillary action or blown in by concentrated jets of air.

Test Method

A glazed window of outer size 120 x 120 cm is mounted in an air tight panel where the joint between frame and panel is sealed. The water leakage, if any, will therefore occur through the window construction. The whole panel is fastened to the opening of an air and water-tight test chamber and pressed against a gasket fixed to the edges of the opening. An air current provided by a fan is led to 16 metal blowers through rubber hoses. Water drops coming from nozzles in a water trough fall down as a result of the air currents, hit slanting brass plates, split up, and are blown against the test panel by the air currents. Both water nozzles and blowers are mounted to a motor driven carriage moving up and down in front of the test panel with the speed of approx. 130 mm/sec. The amount of water hitting the panel is 17 l/m^2h and wind speed from the blowers varies between 10-42 m/sec., with 6 gusts of wind every minute. Corresponding superpressure inside the chamber is 2-110 mm WC. See Figure 3.

The standard test covers the factors mentioned above lasting for 1 hour, and the requirement for a good window is that no water should penetrate the window construction during the time of testing.

In an additional test, 100 l/mh of water is sprayed at the top of the test panel in addition to all the other factors, in order to simulate running water on a 10 m high wall from driving rain hitting the top of the building.

Water penetrating the window construction is never measured, and the report only states the points of leakage, if any, and the approximate amount of water.

11. Strength and Stiffness

11.1 Resistance to Wind Loading

A window must be able to withstand the maximum wind pressure likely to occur in practice without collapsing, falling out of the wall or reducing the performance in any other way.

Usually a rate of failure based on the overall economy is established, but factors of safety and goodwill must also be considered.

When an acceptable safety factor has been determined, assessment of strength involves strength of transparent material, regional windspeed extremes, and building aerodynamics.

A design wind pressure, based on the 3 sec. gust speed, can be obtained from the local building code by a suitable set of factors.

Test Method

The window is mounted in the same apparatus as for testing of air tightness. If the air leakage exceeds the capacity of the fan, all joints are sealed. The object of this test is to find the maximum pulsating wind-load the construction can take without causing collapse or permanent deformation such that the total performance is reduced.

The loading is induced by a fan that can simulate a wind gust every 10 sec. The maximum pressure can be obtained in 3 sec. and can be adjusted from zero to an optimum value of 250 mm WC. The whole sequence can be repeated over a period of time.

11.2 Operating Forces

(a) Horizontal point load

The act of opening and closing a window may cause warping of the light, especially if three of the corners are jammed.

(b) Blocking

When closing and opening the light there may be something stuck between the sash and frame tending to block the window in an open position. If this happens, there is a risk of breakage of the glazing, and hinges and pivots may be damaged.

(c) Friction

The movements of an opening light can to a certain extent be controlled by the use of friction hinges or pivots. The degree of friction must be adjustable and the hinges should be protected against climatic attack. The mechanism must be designed so that it cannot easily be tampered with.

(d) Slamming

Normal opening or closing of a light does not cause any extraordinary dynamic loading. However, it may be blown by a strong wind or closed very hard, and should therefore be able to withstand a dynamic load due to slamming without collapsing or causing undue damage.

11.3 Accidental Forces

(a) Concentrated Dynamic Load

The glazing units must be able to resist the dynamic force from small sharp bodies that may be thrown or blown on to the window. The breaking strength must be evaluated taking into account the initial cost and replaceability.

(b) Vertical point load

The downward force on the outer stile of a light opening by rotation about a vertical axis is intended to represent the accidental load which might occur. During the test the window is opened 90° or to the position which gives the highest effect of the specified load.

The following loads are recorded:

50 kgf - No failure or permanent deformation permitted.
100 kgf - Small permanent deformation permitted, but the opening light must not be torn away from the hinges or collapse in any other way.

12. Control of the Opening Light

After the window has been installed at the normal height above the floor, it should be convenient and safe in use. The possibility of the opening light coming into uncontrolled movements should be kept in mind.

If the window is to be used in places where there is a danger of someone falling out, it should have a fitting which limits the initial opening to 100 mm.

Sharp or rough edges are liable to cause personal injury. Hinges and handles must be designed so that all operation and handling can be done safely.

All cleaning and maintenance should be carried out from the inside unless special precaution is taken so that it can be safely done from the outside.

13. Security against Illegal Entry

To give reasonable security against unlawful entry the locking points of opening windows should be designed so that they are difficult to unlock from outside without having to break the glazing.

14. Fire Resistance

Materials used in the construction of windows should give sufficient safety against fire and spread of fire with due consideration of use, adjacent buildings, and conditions in general.

Ordinary window glass has very little or no resistance to fire. It can be strengthened by the use of wire reinforcemant or double glazing, with frames and sash of fire resistant material.

15. Escape from Fire

In certain cases an opening window may be used as an emergency exit and should be dimensioned accordingly.

16. Appearance

The esthetic effect a window can have is in many cases considerable. Factors like shape, size and surface treatments, together with the location in the building, can raise the value of the building and should be given due consideration.

17. Dimensions

The overall dimensions of a window should match with those of other building components in a co-ordinated metric system where the planning module preferably should be 3 M(30 cm).

18. Durability of Operating Parts

The lights of an openable window should be capable of withstanding cycles of opening and closure based on a certain number of cycles per annum.

19. Durability of Materials

The lifetime of a particular window is determined by climatic and environmental factors and depends on material, construction, and maintenance. Given normal maintenance, the appearance should not be damaged by oxidation or the formation of rot.

Changes in temperature and humidity cause movements to take place which act on the appearance, durability, and strength. The window should therefore not be impaired by variations in temperature and humidity.

19.1 Assessment of Sealed Glazing Units

Sealed glazing units is a common term for different types of factory-made products, consisting of two or more sheets of glass, separated by dehydrated air or gas and with an airtight and vapourtight seal along the edges. The purpose of such units is to prevent condensation, glass soiling and dust and dirt accumulation between the layers of glass. Satisfactory performance is therefore dependent on a sufficiently air and vapourtight seal (3)[1].

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[1] Figures in brackets indicate the literature references at end of this paper.

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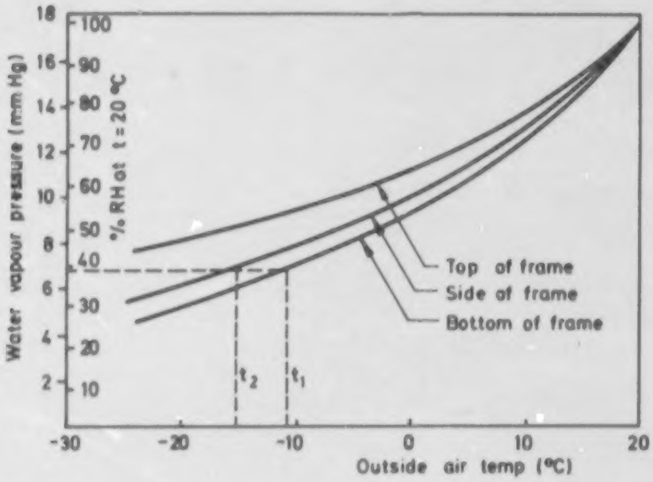

Figure 1 - Condensation on glass, sash and frame.

The curves give the indoor water vapour pressure at 20°C at which condensation takes place depending on the outside air temperature.

Example:
At 40% RH and 20°C in the room condensation takes place on the bottom frame at outside air temperature of t_1 or below, side of frame t_2 or lower etc.

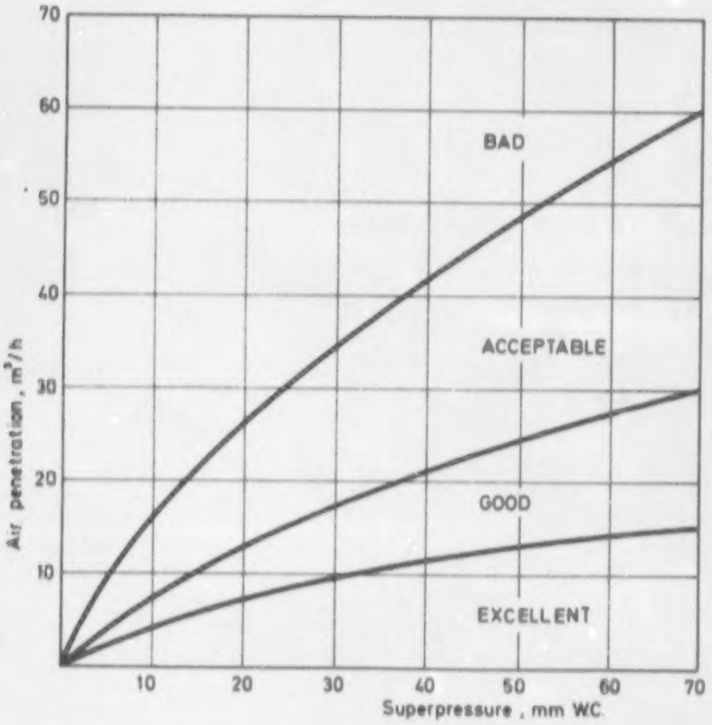

Figure 2 - Classification for air-tightness.

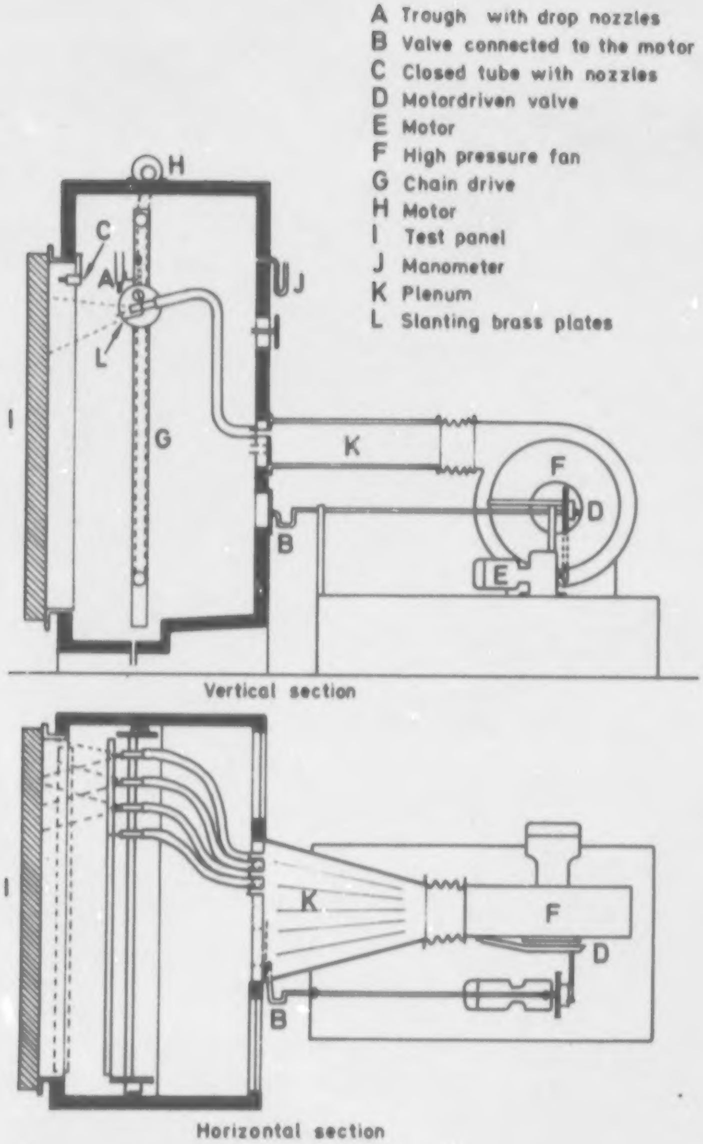
A Trough with drop nozzles
B Valve connected to the motor
C Closed tube with nozzles
D Motordriven valve
E Motor
F High pressure fan
G Chain drive
H Motor
I Test panel
J Manometer
K Plenum
L Slanting brass plates
H
C
A
J
L
I
G
K
F
D
B
E
Vertical section
I
K
F
D
B
Horizontal section

Figure 3 - Driving rain apparatus.

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Evaluation of Window Performance

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Windows are used in the enclosure of buildings to permit entry of natural light, a view of the outdoors, and ventilation. In addition, windows must perform the same function of separating interior and exterior environments as the remainder of the enclosure. Functions related to transparency may be in conflict with those relating to other desired attributes of the building space; this creates the need for considering cost versus benefit on a system basis in establishing performance criteria. This paper deals with the current status of evaluation of windows as environmental separators.

Many aspects of performance cannot be adequately predicted from basic principles, hence a number of standard tests are evolving for evaluation of some of the primary ones. The tests are widely used in product standards, along with relevant criteria, to classify windows and to define certain minimum requirements. Standard test methods, however, have some important limitations in relation to predicting and specifying performance in-use. Some performance characteristics, particularly those involving heat and mass flow, are interdependent although they are usually evaluated independently or are influenced by factors that are excluded or fixed in standard test methods. Where in-use performance of windows is critical, it may be necessary to resort to more complex tests that attempt to take account of all the major factors influencing the final result. This is economically practical only on major construction projects. The development of information to assist the designer in predicting window performance for the majority of situations, utilizing data obtained from standard tests, is, therefore, a desirable goal. The designer will, however, always need to exercise judgment in relating the limited information provided by tests, or other methods of prediction, to the real situation.

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[1] Assistant Director and Research Officer, respectively.

Les fenêtres sont utilisées dans le pourtour des bâtiments pour permettre l'entrée de la lumière naturelle, la vue vers l'extérieur et la ventilation. De plus, les fenêtres doivent accomplir la même fonction de séparer les environnements intérieurs et extérieurs que le reste du pourtour. Les fonctions relatives à la transparence peuvent entrer en conflit avec les fonctions relatives aux autres attributs désirables de l'espace du bâtiment; ceci crée le besoin de comparer le coût au bénéfice d'un système de base en établissant les critères de performance. Cette communication traite du statut actuel de l'évaluation des fenêtres en temps que séparateur de l'environnement.

Plusieurs aspects de performance ne peuvent pas être adéquatement prédits par des principes élémentaires, et un nombre de ces essais normalisés sont, par conséquent, développés pour l'évaluation de quelques normes de matériaux, avec les critères relatifs pour classifier les fenêtres et définir certaines exigences minimales. Les méthodes d'essais normalisés, cependant, sont grandement limitées en relation de la prédiction et de la spécification de la performance désirée. Certaines caractéristiques de performance, particulièrement celles mettant en cause la chaleur, les fuites d'air et les fuites de vapeur d'eau sont interdépendantes, même si elles sont normalement évaluées indépendamment ou qu'elles sont influencées par les facteurs qui sont exclus ou constants dans les méthodes d'essais normalisés. Là où la performance des fenêtres en place est critique, il peut être nécessaire d'en revenir à des essais plus compliqués qui essaient de prendre en cause tous les facteurs importants influençant les résultats finals. Ceci est économiquement pratique seulement lorsqu'il s'agit de projets de construction importante. L'élaboration de renseignements suffisants qui permettent la prédiction de la performance des fenêtres pour la majorité des situations, en utilisant les renseignements obtenus des essais normalisés, est par conséquent un but désirable. Le concepteur devra, cependant, toujours exercer un bon jugement en établissant un rapport entre les renseignements limités obtenus par des essais ou par d'autres méthodes de prédiction et la situation réelle.

Key words: Performance criteria; performance evaluation; window characteristics; window evaluation; window functions; window requirements; window standards.

The primary function of spaces in buildings is to provide an environment appropriate to the activity or process they are intended to serve. Performance requirements for windows and other elements of the building envelope are dependent upon the desired attributes of the space with which they are associated. Windows are an unusually important component of the exterior envelope of many modern buildings in that a number of the desired interior environmental characteristics of the space are dependent upon, or are limited by, the physical nature of windows, as well as their size and disposition. These environmental attributes may involve physical, physiological, and psychological considerations. Window requirements related to one attribute may be in conflict with those for another. Furthermore, many requirements for windows relating to their physical

properties can be specified in terms of identifiable physical parameters and are amenable to objective evaluations, while those that relate to aesthetic and psychological considerations cannot be dealt with rigorously. This presents a great challenge to the effective application of the performance concept.

This paper describes some of the conflicts between different desired attributes of the space, as affected by windows, and reviews the status of procedures for evaluating the physical characteristics of windows, particularly in relation to interior environmental conditions.

The primary technical function of the building envelope is to provide for the separation of certain elements of interior and exterior environmental conditions. Generally, it must resist heat losses to the exterior under winter conditions and heat gains from the exterior under summer conditions in order to optimize total heating and cooling costs; and to ensure that interior surface temperatures can be maintained within limits that provide acceptable mean radiant temperature conditions from the standpoint of human comfort or process requirements [1, 2][2]. It must also provide interior surface temperatures that are generally above the dew point temperature of the interior space to avoid excessive condensation on these surfaces [3].

The enclosure must limit infiltration of outside air under pressure differences caused by wind action and building stack action for economy of air-conditioning and reduction of entry of airborne pollutants. Similarly, it must resist the penetration of water under extreme conditions of driving rain; and increasingly, is expected to reduce the penetration of noise from external sources.

In addition, the envelope must have those characteristics required for it to fulfill its primary functions throughout its intended service life. This includes control of heat and moisture movements so as to avoid deleterious effects associated with excessive moisture contents, e.g., structural damage due to freezing, or loss of thermal resistance. There must also be provision for accommodation of movements due to expansion and contraction of components, or from other causes, without the occurrence of damage. Resistance to loss of performance caused by chemical and physical changes due to ageing processes is another overriding requirement. Finally, the envelope must make its appropriate contribution towards the structural and fire-safety attributes of the building.

A window, including its interface with adjacent components, has the same general performance requirements as the remainder of the building envelope. It has one additional primary requirement, that of transparency. At one time this was mainly for the admittance of natural light. Often, nowadays, it is to provide a view of the outside, which in most instances is to cater to a real or assumed psychological need; or it may be to achieve some aesthetic objective. In some cases transparency of the enclosure may be absolutely essential to the function of the space, as with airport control towers or display windows.

Where adjustable openings to the outside are needed in the building envelope for natural ventilation, windows may be required to serve this function as well. Openability may also be a desired attribute to provide access to exterior window surfaces for cleaning or replacement of glass, for emergency egress, or for building venting in the event of fire.

These special requirements of windows introduce some unique problems and considerations in enclosure design. Transparency to solar radiation can result in conditions of thermal as well as visual discomfort for occupants directly exposed. Solar heat gains through windows may also represent a significant incremental air-conditioning cost [4], or may cause excessive rise in interior temperature where cooling is not provided and ventilation is inadequate. Glazing arrangements and shading devices used to control glare and solar heat gain may substantially increase the cost of fenestration [5].

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[2] Figures in brackets indicate the literature references at the end of this paper.

Transparency in windows is generally achieved through the use of glass. While having a number of advantageous properties, glass has other properties that place severe limitations on certain aspects of window performance. Glass has a relatively low resistance to heat transfer in practical thicknesses. Windows with single glass, therefore, have a high over-all heat transmission coefficient, and thus high heat losses in winter. The low thermal resistance of single glass also produces low interior surface temperatures in winter and discomfort to occupants due to the consequent reduction of mean radiant temperatures. Low surface temperatures also require maintenance of low interior humidity in winter to avoid excessive condensation on interior surfaces.

Multiple glazing arrangements can be used to improve window thermal performance and may also be economically justifiable. Multiple glazing, however, presents some special problems and, therefore, some special performance requirements. Condensation between panes in winter, due primarily to air exfiltration, is a potential problem [6]. Where the pressure difference for exfiltration is large, as in the upper parts of high buildings, hermetically sealed glazing arrangements may offer the most practical approach. Hermetic sealing, however, presents its own difficulties and performance requirements uniquely related to the product [7]. Realization of the full benefits of multiple glazing requires that the thermal resistance of sash and frame members should be at least equivalent to that of the glazing [8]. Double or even triple glazing does not provide thermal performance equivalent to the optimum for opaque parts of the enclosure under similar climatic conditions.

Glass may also present breakage problems due to its brittle nature. Normal design procedures provide for a low probability of breakage due to wind-induced stresses [9]. Breakage problems can occur, however, due to thermally-induced tensile stresses at the edges, which are weakened by stress-raising imperfections [10]. Thermal stresses leading to breakage can be induced by absorption of solar radiation, or by interior heating combined with a number of other factors that may go beyond the design of the window. Breakage may be attended by hazards to nearby persons due to falling glass, especially in the case of multi-storey buildings fronting on pedestrian ways.

Finally, it might be noted that the requirement of openability introduces articulated joints, and therefore amplifies the problem of providing and maintaining weathertightness. In addition, it introduces requirements related to ease of operation and serviceability of hardware.

1. Window Performance Criteria

Establishing performance criteria for windows introduces almost all of the considerations that can arise in application of the performance concept to building design. The first question is whether or not to use windows at all, and for what reasons. Where they are being considered for purposes of natural lighting or ventilation, a relatively rigorous technological basis can be established for determining minimum amounts and optimum disposition of glazing and openable areas. If there are no other reasons for their use, an economic comparison of alternative solutions involving luminaries and air-conditioning should be made. Where psychological and aesthetic considerations are involved, an attempt should be made to come to some logical conclusion on minimum areas and acceptable arrangements for these purposes. Here the judgments are largely subjective, or depend upon expectations or desires of the client or user based on tradition or current fashion.

Once the decision to employ windows has been made, the question of the required level of performance for the various attributes must be faced. Criteria involving safety will usually be rigidly established by building codes, e.g., glass thickness requirements to control the probability of glass breakage under extreme wind loads, or limitations on the amount and distribution of glass relative to the spread of fire to adjacent buildings by radiation. For most of the other attributes, the levels of performance required are not, in principle, rigidly fixed but can vary over a range and relate to the specific design situation. In practice, the extent of choice is limited by the nature of the products available at any time; conversely, certain minimum levels of performance may be established by product standards.

Choice of criteria involves cost versus benefit considerations or compromises in criteria where various attributes are in conflict. For example, the use of large areas of single or even double-glazed windows produces less than optimum thermal comfort conditions near the glass under certain summer and winter conditions. Therefore, rigid application of a rigorously based thermal comfort standard would greatly restrict the amount and disposition of windows for such conditions, limit the utilization of space adjacent to the window, require window arrangements providing superior thermal performance, or would require devices to provide compensatory radiation.

Similarly, consideration of heating and cooling costs would lead to the conclusion that window areas should be severely restricted or eliminated in many applications. This might well be in conflict with a desire for natural light, or with psychological and aesthetic considerations, so that trade-offs must be made. In making choices involving such subjective judgments, the cost and other performance implications should be fully recognized. Relatively sophisticated methods, involving the use of digital computers, are now becoming available for predicting the heating and cooling loads of buildings throughout the annual weather cycle, and can be utilized to determine the effects of window choice [11]. Such computations would be justified for major projects; generic information is required for smaller ones.

The spatial variation in mean radiant temperature in the vicinity of windows is also amenable to computation, and it would be helpful to have this available in a convenient form for various wall-window and room arrangements and temperature conditions. These are aspects of windows that must be evaluated in terms of their interaction with the building or space. The following section deals with evaluating the physical properties or characteristics of window units in the context of North American practice.

2. Evaluation of Physical Performance Characteristics

Performance characteristics related to the transparency of windows are the light transmittance, the total solar transmittance and the shading coefficient [12]. Light transmittance is measured with a photometer in natural sunlight; total solar transmittance is measured with a radiometer. The shading coefficient is an index of total solar heat gain through a window. For simple arrangements it can be calculated from measured solar transmission and absorption coefficients of the glazing and assumed values for the surface and air-space thermal resistance. Where shading devices are involved, a calorimeter must be employed. Data for many common arrangements are available.

Air-infiltration and air-exfiltration characteristics of a window can be determined by a nationally recognized standard test method issued by the American Society for Testing and Materials (ASTM) [13]. Maximum values are specified in many product standards.

Rain-leakage characteristic can be determined by a variety of laboratory test methods that can be categorized as: those simulating the dynamic action of wind; and those simulating wind action by means of a static air pressure. The static rain-leakage test method has been standardized by ASTM [14]. The dynamic test method has not been standardized, but most facilities are similar in that they utilize an aircraft engine and propeller to simulate wind action [15]. The more appropriate method to use for evaluating the leakage resistance of a particular window depends on the design of the joints [16].

The cold-weather thermal performance of a window is described by the over-all heat-transmission coefficient (U-value), the inside-surface condensation resistance, and, in the case of an operable double window, the interpane condensation resistance. The U-value of a window can be determined by the standard ASTM Guarded Hot-Box Test [17]. Data adequate for most purposes are available [12].

There is, at this time, no nationally recognized standard method for determining the resistance of a window to inside-surface condensation. Adequate prediction of inside-surface temperature in the vicinity of frames and sash by computation is not practicable as yet. The Architectural Aluminum Manufacturers' Association has, however, developed a simplified test for comparing the inside-surface temperature performance of metal windows. Standardization of this method in a modified form is currently being considered by ASTM [18]. The test conditions used are not representative of those found in practice, and the test results are, therefore, not indicative of performance in service.

A number of laboratories in the U.S. and Canada have, for many years, been conducting cold-room/warm-room tests to determine the condensation performance of metal windows under simulated cold-weather conditions; one such test is described in Canadian metal window standards [19]. This type of test, conducted under more realistic conditions, provides a better prediction of the surface temperature performance of a window in use; where better prediction is required, it is necessary to simulate in the assembly all of the components that have a significant influence on surface temperature, including adjacent wall construction, interior shading devices, and the air-conditioning terminal unit. This approach is only practicable for major building projects. It is desirable, therefore, to develop information that will assist in prediction of in-use performance of arrangements commonly employed utilizing data obtained from standard tests.

No standard test method exists for determining the interpane-condensation resistance of operable double windows. This characteristic, which is dependent on the thermal and air-leakage performance of a window, can, however, be evaluated in a cold-room/warm-room test facility if realistic room-side relative humidities and air-pressure differences to induce air exfiltration are provided [20].

A standard ASTM test method i available for measuring the resistance offered by a window to airborne sound transmission [21]. Windows generally offer less resistance than other elements of the enclosure and can, therefore, be of special importance in determining the influence of exterior noise on interior sound levels.

The foregoing indicates that test methods are available for evaluating all of the performance characteristics of a window related to its environmental separation functions. Methods are also available for evaluating some of the window characteristics related to strength and durability.

High winds acting on a window can blow the glass out of the glazing rabbet or can deflect window members sufficiently to cause permanent deformation. A standard ASTM test method is available for determining the resistance of a window to glass blow-out and member deflection due to uniform wind loading [22].

The deflection of sash members due to concentrated loading imposed when the sash is opened and closed is another structural performance characteristic that can be evaluated by test. As sash operation differs from one window type to another, each type is evaluated by a different method [19, 23, 24].

Glass breakage can result from mechanical stresses such as those produced by wind action, or from thermal stresses such as those produced by the absorption of solar radiation. The resistance of glass to breakage by mechanical stress is usually dependent on the surface strength of the glass, whereas the resistance to breakage by thermal stress is dependent on its edge strength.

The breakage resistance of a window to wind loading is rarely evaluated by test because of the variable nature of the breaking strength of sheet glass. To provide a sufficiently low probability of failure, the values of glass thickness and area recommended by the glass manufacturers for the anticipated wind loads, or those dictated by the local building code, are normally used. The panes of a sealed double-glazing unit experience an additional mechanical bending stress due to volume changes of the air space caused by changes in barometric pressure and air temperature. The force produced depends on air-space thickness and can be calculated, although such an analysis is rarely performed. With units as normally fabricated, the maximum stress due to this force is less than that caused by the design wind load.

Predicting the thermal-breakage resistance of glazing is difficult because neither the edge strength of the glass nor the thermal stresses can be readily established. A procedure for selecting glass sizes to control breakage of single heat-absorbing glass due to solar radiation has been developed by one manufacturer, but the basis for it has not been published [25].

Predicting the thermal-breakage resistance of sealed double-glazing units incorporating heat-absorbing or heat-reflecting glass, is further complicated because both panes are susceptible to breakage [10]. Failure of the outer pane is normally caused by differential absorption of solar radiation during cool weather; although the factors causing breakage are known, there is no established method for evaluating its breakage resistance. Breakage of the inner pane of a sealed unit is usually caused by differences in heat loss between the edge and centre in cold weather. An indication of the potential for this type of breakage can be obtained by surface temperature measurements in a cold-room/warm-room facility, providing the terminal heating unit and the inside shading device to be used with the window are included.

The performance characteristics associated with the durability or service life of a window are the most difficult to evaluate. There is currently no test method for subjecting whole window assembly to accelerated weathering and wear. There are, however, test methods for determining the durability of some of the constituent parts of the window.

Accelerated laboratory tests are available for evaluating the quality of the seal of sealed double-glazing units [26], and a number of test methods are available for evaluating the weathering resistance of glazing compounds and sealants [27, 28]. Test methods are available for determining the wear resistance of sash balances and one type of sash operator, and for determining the durability of pile-type weatherstripping [29, 30, 31]. At present, there are no methods in general use for determining the durability of window components such as plastic and metal weatherstripping, or many of the sash operators.

While the development of performance-type tests for window evaluation is relatively well advanced, the tests' inherent limitations must be recognized. Several aspects of window performance, particularly those relating to thermal implications, are interdependent and, furthermore, depend on a large number of factors and conditions existing on site many of which, for obvious practical reasons, are either excluded, simplified, or fixed in standard test methods. The relevance of the information obtained must, therefore, be carefully assessed in relation to the specific application.

3. Current Status of Window Standards

Window standards in North America have, until recently, contained only minimum performance requirements for different types of windows [19, 24]. An attempt is now being made to classify windows as to quality, based on different levels of performance rather than on window type.

One criticism that can be directed at nearly all window standards is that they are not comprehensive. Physical performance requirements such as glass-breakage resistance, inside-surface and interpane condensation resistance, heat-loss resistance and noise transmission resistance are rarely included.

The primary benefit to the building designer of window standards is that the performance requirements they contain are a useful guide to the performance readily obtainable with existing windows. These requirements, however, must not be interpreted as being sufficient to ensure adequate in-use performance in all respects.

4. Conclusion

Windows may be essential for certain desired attributes of the building space while adversely affecting others. Thus they are a good example of the compromise involved in building design and of the importance of a conscious weighing of cost versus benefit in establishing performance criteria. While window technology is relatively well advanced, there are still areas in which the ability to predict performance in-use is not adequate. This applies especially to evaluation of certain aspects of thermal performance, including susceptibility to breakage from thermally induced stresses, and to prediction of service life of components.

Development of window standards based on performance characteristics and standard test methods has proceeded steadily in recent years, and has resulted in the general acceptance of certain minimum levels of performance. While these standards do not deal with all important characteristics, they do provide the designer with a good starting point for specifying window requirements. Where in-use performance is critical, and directly applicable experience is lacking, special tests can be employed that attempt to take account of conditions that obtain in the specific application. There will, however, always be a disparity between the conditions of the evaluation and those in use, requiring the exercise of careful judgment by the designer. The further improvement of test methods and other evaluative techniques, and the development of information to assist in the prediction of window performance are desirable objectives.

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Effect of Envelope Design on Cost Performance of Office Buildings

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Building design ideally should cover a sufficient range of design alternatives to enable selection of a combination of the performance variables which is as near optimum as can be obtained with the money available. In practice most design variables do not relate simply to the performance variables, and the best that can be done is to check the various performance levels of a design selected on the basis of past experience, amending those features found to be unsatisfactory. This conventional procedure can be improved as much by the development of suitable computational routines as by further refinement of direct measurement of performance.

This paper reports substantial progress with the computation of air-conditioning costs, which when both initial and operating costs are taken into account is the biggest cost item in an office building. The peak air-conditioning load, the sum of the initial costs of the plant, and the envelope plus plant operating, maintenance, and replacement costs over the life of the building have been calculated for 122 variations of a hypothetical building situated in Melbourne (38°S, 145°E).

The study showed that the return on investment could be increased from 10% to over 11% for a hypothetical building with 150,000 sq.ft of rentable space depending on envelope design. For smaller buildings this increase could be even higher because the ratio of the envelope area to volume of the building increases as volume decreases.

Tables and graphs are presented which give some consideration to the relative economic effectiveness of building envelope materials and fenestration.

Les projets de construction, idéalement, devraient comprendre une gamme suffisante de projets alternatifs afin de permettre la sélection d'une combinaison aussi optimale que possible des variables de performance dans les limites de l'argent disponible. En pratique la plupart des variables des projets ne se rapportent pas simplement aux variables de performance, de sorte que la meilleure chose à faire

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est de vérifier les divers niveaux de performance d'un projet choisis sur la base d'une expérience antérieure, en corrigeant les éléments qui laissent à désirer. Cette méthode conventionnelle peut être améliorée autant par le développement de méthodes de calcul convenables que par une plus grande finesse de la mesure directe de la performance.

Cette communication rend compte des progrès substantiels faits dans le calcul des coûts de climatisation, qui est le poste le plus coûteux de la construction des bureaux, si les frais initiaux et de fonctionnement sont pris en considération. Le maximum de charge de la climatisation, la somme des frais initiaux de l'installation et les frais de fonctionnement, d'entretien et de remplacement de l'enveloppe du bâtiment et de l'installation pour la durée du bâtiment, ont été calculés pour 122 versions d'un bâtiment hypothétique situé à Melbourne(38° s, 145° E).

L'étude a montré que, suivant la conception de la coque, le rapport de l'investissement pouvait être augmenté de 10% à plus de 11% pour un bâtiment hypothétique de 150,000 pieds carrés d'espace à louer. Pour des bâtiments plus petits, l'augmentation pourrait être encore plus grande puisque le rapport de la surface de l'enveloppe au volume de bâtiment augmente à mesure que le volume décroît.

Des tableaux et des graphiques sont présentés qui donnent une certaine appréciation de l'efficacité économique relative des matériaux et ouvertures de l'enveloppe d'un bâtiment.

Key words: Cost analysis; design criteria; external envelope; office building; performance evaluation.

1. Introduction

Buildings have many performance attributes, the importance of each varying according to the purpose(s) for which a building is used. The quality of a building as a whole depends on the combination of attributes which designers and contractors have achieved, but unfortunately there is no all-inclusive relationship from which a quantitative evaluation of the whole building, in terms of end uses, can be obtained by inserting the performance level of each single attribute. Even worse, the individual attributes cannot be determined by measuring a single physical quantity, most of which are themselves complex concepts. For example thermal comfort conditions depend on air temperature, movement, and humidity, radiant heat exchange, and the human body's immediate past history of exposure to these factors, thus bringing climatic conditions prevailing outside the building into consideration. Although an index has been developed for evaluating instantaneous thermal comfort conditions in terms of air temperature, humidity, and movement, evaluation of a built space has to be a rather subjective appreciation of how frequently uncomfortable conditions will occur within a stipulated seasonal cycle, and the cost of this level of avoiding discomfort. Proper judgment of the cost evidence depends on two further sets of information - cost allocations for other functions of the building, and cost sensitivity for increasing or decreasing the present level of thermal comfort. In theory, cost for performance is the common measure of effectiveness by which the building designer compromises one function against another. In practice, the work required to assemble data and perform computations restricts the design process to little more than checking the costs and some of the performance levels resulting from a set of "experience-based" choices of building elements and equipment. Should the results show the design to be too costly or markedly uneven in performance, the fewest possible of these choices are changed (again on the basis of experience) and recalculated.

If the data gathering and computations could be automated to allow the designer to explore readily the variation of performance resulting from choices from a range of elements and equipment, and simultaneously see the overall as well as the detailed cost consequences, then design for performance might become a viable proposition. Using related computer programs for air-conditioning load and economic calculations, this paper describes how design changes of one building element, the envelope, are reflected in initial and operating costs, taking into account initial envelope costs and total costs of air conditioning.

The cost of air conditioning for office buildings can amount to more than 20% of the total capital cost (1)[1], the plant needs to be replaced during the life of the building, and the annual operating and maintenance costs may reach 2% of the total capital cost of the building. It is not surprising therefore that on a present worth basis up to 40% of the costs of erecting, operating, and maintaining the building (not including fees, rates, taxes, and interest payments) can be attributed to the air-conditioning installation. This makes air conditioning the biggest single cost item and consequently of great concern to the owner.

It is shown that by selecting a suitable design and shape of the building envelope the architect can influence the size of the peak air-conditioning load by over 30% and hence the capital cost of the building by up to 7½%. The net effect of this would be to increase the return on investment by 1%.

A hypothetical 20-storey office building in Melbourne was chosen as a control and a large number of variations in area of glass, design of fenestration, and building size, shape, and height were analysed by computer. Nevertheless, because the study is limited to variations about one building, in one location, and with several fixed assumptions as to internal structure and internal loads, only very rough rules of thumb can be deduced to be of use in the general case for preliminary planning exercises. In consequence, for any particular project this study shows primarily that computer-assisted examination of alternatives at some early stage of the design process is necessary and worthwhile. Clearly the programs used here could ultimately be part of a kit whereby tentative design choices as to each building element can readily be determined in terms of cost and performance.

In this study the computer program used for calculation of the air-conditioning load is based on the harmonic method for calculating heat flows in buildings (2) and later refinements to the method by Muncey and Spencer (3) (e.g. allowing solar radiation to be absorbed by the floor). An important feature is the ability to allow for the heat storage capacity of all internal and external parts of the building.

2. Definitions

Building envelope:	External walls including fenestration treatments and roof.
Glazing ratio:	Ratio of area of glass to total area of external wall including glass. (This is applied only to individual building faces and is often expressed as a percentage).
Plan ratio:	Ratio of length of north wall to length of west wall (building assumed rectangular). Plan ratios greater than one thus denote buildings with their long sides facing N* and S*, while plan ratios less than one refer to buildings with their long sides facing E* and W*.

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[1] Figures in parentheses indicate the literature references at the end of this paper

Shading coefficient (SC): Ratio of the solar heat gain through any particular fenestration to the solar heat gain through a single pane of 1/8-in. clear glass of the same area.

Horizontal sun break: Horizontal projection placed above a window to provide partial or complete shading from direct sunlight. Sunbreak rating H = ratio of width of sunbreak perpendicular to wall, a, to vertical height of bottom of window below sunbreak, b, expressed as a percentage;

$$H = \frac{a}{b} \times 100\%$$

3. Abbreviations and Symbols

The following abbreviations are used:

A/c = Air conditioning
sq. = Square = 100 ft^2
r.sq. = Rentable square = 100 ft^2 of rentable floor area
D = Double leaf wall consisting of 11 in. cavity brick plus 1 in. plaster render
S = Single leaf wall consisting of 4 in. concrete plus 1 in. plaster render

The following symbols are used.

C_i, Australian dollars/r.sq. = Sum of capital cost of building envelope plus capital cost of installed air-conditioning plant divided by number of rentable squares
C_t, Australian dollars/r.sq. = Sum of C_i plus plant replacement costs discounted to present worth plus plant operating and maintenance annual costs discounted to present worth over the life of the building divided by number of rentable squares
P_r, tons of refrigeration/r.sq. = Capacity of installed air-conditioning plant in tons divided by number of rentable squares (1 ton of refrigeration = 12,000 Btu/h of cooling)
N* = Building face most nearly facing north; actual bearing north 20° west

Similarly:

S* = South 20° east
E* = North 70° east
W* = South 70° west

4. Scope of the Study

The peak air-conditioning sensible load for 122 hypothetical buildings was calculated and a comparison of the relative economics of the different solutions was then made. The economic factors taken into account were the initial costs of building envelope and air-conditioning plant, plus plant replacement and other plant-owning costs over the life of the building.

A single building with gross area of 235,000 ft^2 was selected as the standard, known hereafter as the control building, as detailed in Table 1.

The size and height are compatible with actual office buildings in Melbourne; February climatic data are assumed (maximum temperature, 101°F), and the orientations are such that the sides are perpendicular and parallel to the bearing N20°W. This conforms to the Melbourne city street grid.

The 122 variations on the control building can be grouped in the following classes:

(a) Size. Size was varied between 40,000 and 325,000 r.sq.ft.

(b) Shape at Constant Size. In some cases, for constant height the aspect ratio of the control building was varied between 1 and 3, in others the height was varied with constant plan ratio between 10 and 25 storeys.

(c) Glazing Ratio. Keeping all other parameters constant glazing ratios were varied face by face between 20% and 60%.

(d) Fenestration. In some cases shading coefficients were varied face by face, in others horizontal sunbreaks were varied, and in others combinations of shading coefficient and sunbreaks were studied with both differing from those of the control building.

(e) Wall Type. About half of the buildings had exterior walls of 11 in. cavity brick and half of 4 in. concrete.

(f) Orientation. In many cases, with all other parameters constant buildings were analysed with their longer sides facing N* and S* and then with their longer sides facing E* and W*.

In each case the peak sensible load was calculated assuming that daytime indoor temperature was maintained at 75°F, an allowance for latent heat of water vapor removed was then added, and the total was multiplied by 1.3 to arrive at a figure for plant capacity actually installed. The factor 1.3 was selected since this conformed closely to the ratios of installed and calculated capacities actually observed in a sample of office buildings recently erected in Melbourne[2].

The assumptions underlying the economic calculations are given in Table 2, the rates given in that Table being based on data supplied by various industry sources.

Plant capital cost rates are a function of size (Table 2) and represent averages between simple and sophisticated solutions. It is assumed that plant operating and maintenance costs are proportional to P_r and hence minimum total air-conditioning costs (although not necessarily C_i and C_t) are obtained with minimum P_r.

In fact, two buildings with the same peak air-conditioning loads may not have the same total load when integrated over the year, e.g. one building may be better protected than the other against low altitude sunshine on the north face during spring and autumn. The type of plant and mode of operation also affect the relation between capital and total costs. These refinements require further study, and in this regard the program for estimating the air-conditioning load has considerable scope not utilized in this study. For example, the economic effects of designing for any indoor temperature different from the 75°F assumed here can be quite readily studied.

5. Results

Lack of space makes it impossible to detail all the results, but the selection given should illustrate the main contention that for any office building project it is well worthwhile to evaluate a wide range of practicable envelope designs in economic as well as performance terms.

Although a larger number of cases was investigated, the best example of this is seen in the 98 designs for buildings of about 1500 rentable squares. The highest, lowest and control building values for P_r, C_i and C_t obtained were:

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[2] Presumably 30% excess of calculated steady condition requirements is what the market is prepared to pay for controllability

	Max.	Min.	Control
P_r (ton/r.sq.)	0.602	0.371	0.544
C_i ($/r.sq.)	740	553	697
C_t ($/r.sq.)	1595	1103	1487

It is not necessarily true that the one design will achieve minimum values for each of the above three parameters. Normally, a compromise which would match an available air-conditioning plant and give close to optimum values of C_i and C_t can be found from the first tabulation. Space prevents presentation of the Table here.[3]

The range in P_r (0.23 ton/r.sq.) is from 68% to 111% of the control building value, in C_i ($187/r.sq.) is from 79% to 106%, and in C_t ($492/r.sq.) is from 74% to 107%. These show that the designer has considerable scope for influencing the size of air-conditioning plant and the overall economics of the project.

The range in C_i ($187/r.sq.) is equivalent to about six months net income from the building assuming that this is $350/r.sq. (see below). A new construction method which advanced completion by six months would be rightly hailed as a major advance; improvement of the economics of envelope design can be just as significant and should be much easier to achieve.

In terms of return on investment if some additional figures are established for the control building then the differentials for costs of air conditioning and building envelope can be used to calculate net returns for any particular configuration.

During 1970 costs of multi-storey office buildings in Melbourne ranged from $16 to $44 per square foot. Costs of $20 would be characteristic for a developer operating in the most competitive segment of the market. Projects of the latter type would achieve an 80% ratio of rentable to gross floor area on typical floors and land and holding charges would be about 40% of building cost, so a reasonable "all investment" cost for the control building would be $3500 per 100 square feet of net rentable area ($3500/r.sq.). Operating and maintenance costs for air-conditioning plant can be taken to average $75 per installed ton per year for a building of this quality.

During 1970 the expected rate of "return on all investment" for the first year of operation of a building was about 10% with all building operating costs, charges, and taxes paid, and provision made for depreciation.

Therefore, accepting that the control building costs $3500/r.sq. overall, provides $350/r.sq. per year of net income (yield of 10%), and that the operating and maintenance cost of the air-conditioning plant is $75/ton per year, then the yield of the 20-storey building with the most economic combination of low C_i ($144 less than the control) and low air-conditioning load (0.166 tons less than the control)[3] is

$$\frac{350 + (75 \times 0.166)}{3500 - 144} \text{ i.e. } 10.8\%$$

while the yield for that with the most expensive combination is

$$\frac{350 - (75 \times 0.040)}{3500 + 44} \text{ i.e. } 9.8\%$$

Thus the overall variation is 1% for a constant building size, which would be regarded in Melbourne as sufficient to make the difference between an uneconomic and a profitable project.

Careful design of fenestration in respect to both cost and shading coefficients should give scope for further reduction of costs because the cost rates assumed in this paper are only average figures. Figure 1 shows the relation between shading coefficient and in-place costs obtained from the industry for various combinations of glass, blinds, and drapes. The scatter is very great. Furthermore, as the study was limited to a comparison between two wall types (4-in. concrete and 11-in. cavity brick) and only a few of the possible combinations of other variables, the 1% between best and worst cases calculated is probably much less than the differences that occur in practice.

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[3] These figures are detailed in a Table available on request to the Division of Building Research, CSIRO

Figure 2 shows the effect on C_t of reducing the ratio of envelope area to floor area. All of the points represent buildings of various shapes and sizes but with exactly the same glazing ratio and fenestration design as the control building. Size has the most effect on the ratio. Nevertheless, changing the shape by varying height with constant size and plan ratio reduced C_i by $114/r.sq. and C_t by $221/r.sq. as the number of storeys was reduced from 15 to 10 for a building with gross area of 60,000 ft^2, and by $84 and $156 respectively as the number was reduced from 25 to 16 storeys for a gross area of 235,000 ft^2. These figures are for brick walls, and they are about 20% greater with lighter walls.

Plan ratio was the other shape variable studied. As plan ratio was reduced from 3 to 1 at constant size and height, reductions in C_i and C_t were about half as big as the figures quoted above.

Each of the buildings shown in Fig. 2 was evaluated by assuming that the long axis lay (a) on a bearing N20°W and (b) on a bearing perpendicular to that. However, only the average of the two orientations in each case has been plotted because the differences in air-conditioning loads required were very small. Thus orientation appears to be of only minor economic significance when the sun control measures are applied equally to all faces for the particular street grid examined. In addition to shape, the quantity of glass, its shading coefficient, its distribution by face, and the degree of sun protection afforded have important economic consequences.

Table 3 (for buildings with heavy walls) shows that reduction of the glass area by 5 (ft^2/r.sq.) on either the N* or W* face reduces the load by up to 0.05 ton /r.sq., saves roughly $50/r.sq. in initial costs, and a little more than $100/r.sq. in total costs. A similar reduction in glass area on either the S* or E* face is only about half as effective in reducing the load and cost.

For buildings with light walls (not shown in Table 3) the above figures over-estimate the reduction by about 25%. Thus the initial cost saving by reducing the glass area in the N* or W* wall by 5 ft^2/r.sq. is roughly $45/r.sq. with the much lighter wall. An analysis was carried out with glass area reduced by 3.88 ft^2/r.sq. on N* and S* faces and by 1.92 ft^2 on E* and W* compared with the control building, for a brick building of plan ratio 2:1 and the long side facing N*. The result is shown on the bottom line of Table 3, and the figures in brackets show the calculated result assuming that the factors in the upper part of the Table are used. Use of the factors provides a result in agreement with the actual result.

Table 4 shows that although reduction in the shading coefficient is less effective in lowering costs than reducing the area of glass, useful reduction in load and total costs are made by adopting window shading coefficients of about 0.4 compared with 0.6 on N* and W* faces. Similar reductions on E* and S* faces are not of great economic significance, but if they are desirable on aesthetic grounds they do not worsen the economic picture.

On the other hand, further reduction in the shading coefficient as far as 0.2 is not justified on economic grounds on E* and S* faces. On N* and W* faces there is still a slight gain on a total cost basis, although initial costs increase.

Table 5 illustrates the reductions in loads and costs resulting from an increase in the horizontal sunbreak ratings on each face. There is always an economic disadvantage in placing any sunbreaks on E* and S* faces. On the N* or W* face sunbreaks of 60% rating can effect load reductions of a little more than 0.04 ton /r.sq., modest initial cost savings of up to $20/r.sq., and useful total cost savings of up to $80/r.sq. A sunbreak rating of 60% was about the maximum needed, and there is very little economic advantage in using a higher rating in this example.

Table 5 indicates that sunbreaks to W* faces are less than half as effective as sunbreaks to N*, but these analyses were carried out only on buildings oriented such that the N* face was twice the area of the W* face. Reference to Table 3 shows that changes of glass area to the N* were also more effective than changes of glass area to the W* with this orientation, but that this was reversed when the W* face was twice the area of the N* face. On the evidence available there is therefore little point in separating the sunbreak effects between N* and W*.

An analysis was also carried out with the changes in sunbreak rating made simultaneously on all four faces. The result is shown in Table 5, from which it appears that the effects of combining sunbreaks on different faces could be gauged closely by adding the separate effects, as the figures in the last line of the Table show.

6. Concluding Remarks

It is common knowledge that reduction in heat gain and costs can be made by careful design of the building envelope; indeed some glass manufacturers have produced charts and tables quantifying the effects of different glazing methods.

Nevertheless, in Australia at least, it has not been usual to quantify systematically the heat gains and resulting alternative costs of envelope design in the manner of this hypothetical study. This is mainly due to lack of time to perform the calculations required, but probably also because of lack of realisation by architects of the true magnitude of air-conditioning costs. Costs-in-use are usually given scant attention, but in the case of air conditioning when taken over the life of the building and expressed as present value they are found to be as high as initial costs.

In this study the maximum variations obtained in P_r, C_i, and C_t were 42%, 27% and 33% respectively of the control building values. Since the marginal effect of reduced operating and capital costs of air conditioning has been shown to change the yield from nearly 10 to nearly 11%, an obvious design strategy would be to insulate outer walls and also use reflective glazing and sun screening to the limit of their effectiveness. Although basically correct,this needs to be qualified, because the calculations producing these figures assume a constant overall building cost of $3500/r.sq., whereas this figure would change according to the levels of insulation, glazing, and sun screening adopted. Tables 4 and 5 show that reduction of air-conditioning load does not necessarily improve C_t. Nevertheless, an additional $5 to $6/ft^2 of facade would have to be spent to reduce the yield by 1% overall, so there is considerable scope for selectively implementing such a strategy.

To enable this,the computational process should include both load estimation and relevant cost calculations. By watching the cost implications of the design changes he makes,a designer will quickly see which measures are most effective under the constraints imposed by that particular location. When testing such changes it must be realized that although consideration of any one aspect of building design in isolation may be helpful, it is certainly not sufficient. For instance, increasing building height has a large number of economic consequences of which those due to an increased ratio of envelope area to floor area are only a few.

7. Acknowledgments

Thanks are extended to the following firms in the building industry who supplied costs and other data: W.E. Bassett and Partners, Oliver Davey Glass Co. Pty. Ltd., and Rider Hunt and Partners.

8. References

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Table 1. The control building

STRUCTURE	Plan dimensions	140 x 70 ft
	Central service core (unconditioned)	50 x 30 ft
	No. of storeys*	20
	Rentable area	150,000 ft^2
	Air-conditioned area	162,000 ft^2
	Plan ratio	2:1
	Orientation	Long side facing N20°W
	Glass area	40% of wall area on all sides
	Window shading coefficient (SC)	0.6
	Horizontal sunbreaks	None
	Wall height (between floors)	10 ft
	Materials of roof	Metal deck, 4 in. concrete, 2 in. mineral wool, plasterboard
	Materials of walls	4 in. concrete, 1 in. hard plaster
	Material of core walls	6 in. concrete
	Material of floors	Carpet on 12 in. concrete flat slab
	Material of ceilings	Plasterboard 12 in. below floor slab
	Partitions, furniture	Each assumed to have surface area of half the air-conditioned floor area
LOADS	Outside temperature	Melbourne, February 24-h cycle peaking at 101°F
	Direct and diffuse solar radiation	February 22nd, clear day
	Internal loads: People	1.25 Btu ft^{-2}h^{-1} convective
		1.25 Btu ft^{-2}h^{-1} radiant
	Lights†	7.5 Btu ft^{-2}h^{-1} convective
		7.5 Btu ft^{-2}h^{-1} radiant
	Ventilation and infiltration	1½ fresh air changes/h

*No. of storeys refers to air-conditioned floors. A further number of up to four floors is assumed for the calculation of gross area.

†Assumed "on" during working day

Table 2. Assumptions made in economic calculations

Item	Rate[*]
Horizontal sunbreaks - if applied they are assumed to run full length of face and are concrete hoods	$\$1.75/ft^2$ of projection
Shading coefficients: 0.93	$\$1.13/ft^2$ of glazing
0.60	$\$1.93/ft^2$ of glazing
0.40	$\$3.40/ft^2$ of glazing
0.20	$\$6.80/ft^2$ of glazing
Allowance for window frame	$\$3.00/ft^2$ of glazing
Ext walls 4-in. concrete + 1-in. hard plaster	$\$2.25/ft^2$
11-in. cavity brick + 1-in. hard plaster	$\$2.25/ft^2$
Roof	$\$1.75/ft^2$
Air-conditioning plant, capital cost for T tons	$\$(1113-0.34\ T + \frac{T^2}{8240})$
Air-conditioning plant, operation and maintenance per year	$75/ton
Discount rate[†]	9% p.a.
Inflation rate for plant replacement and operation and maintenance	3% p.a.
Life of building	40 years
Average life of plant	20 years

[*] Australian dollars used throughout

[†] Example of application of discount rate: The present worth of $500.00 to be spent in 5 years time is $\frac{\$500}{(1+0.09)^5} = \$325.00$

Table 3. Reductions caused by lessening glass area
(Double leaf wall buildings)

Faces to which reduction of glass area applies	Reduction in glass area (ft^2/r.sq.)	Reductions for longest walls facing N* & S*			Reductions for longest walls facing E* & W*		
		P_r (ton/r.sq.)	C_i ($/r.sq.)	C_t ($/r.sq.)	P_r (ton/r.sq.)	C_i ($/r.sq.)	C_t ($/r.sq.)
1. N*	5	0.049	56	125	0.046	49	112
2. E*	5	0.022	33	68	0.021	30	60
3. S*	5	0.019	29	59	0.017	26	54
4. W*	5	0.041	50	108	0.052	54	127
5. (N* & S* (E* & W*	3.9) 1.9)	0.083	99	216	-	-	-
6.[†] N*, S* E*, W*		0.077	98	210			

[†] 5. Values as calculated by the computer program

6. Values approximated by simple proportion for the same case as row 5, by simple proportioning of data in rows 1 to 4. Agreement with row 5 is sufficiently good to allow individual simple cases to be combined in this way

Table 4. Reductions caused by lessening shading coefficients over a glass area of 5 ft^2/r.sq. (Double and single leaf walls)
(Longest wall faces N* & S*)

Faces to which change in shading coefficient applies	Change in shading coefficient					
	0.6 → 0.4			0.4 → 0.2		
	Change in			Change in		
	P_r (ton/r.sq.)	C_i ($/r.sq.)	C_t ($/r.sq.)	P_r (ton/r.sq.)	C_i ($/r.sq.)	C_t ($/r.sq.)
1. N*	0.021	10	40	0.012	-8	10
2. E*	0.013	3	20	0.004	-14	-8
3. S*	0.011	2	17	0.003	-14	-11
4. W*	0.019	8	35	0.010	-9	5

Table 5. Reductions caused by increasing horizontal sunbreaks. (Double and single leaf walls). Glass area = 23% of rentable floor area. Longest wall faces N* & S*

Faces to which change applies	Change in sunbreak rating								
	0 → 30			30 → 60			60 → 90		
	Change in			Change in			Change in		
	P_r**	C_i††	C_t††	P_r	C_i	C_t	P_r	C_i	C_t
1. N*	0.024	12	45	0.020	8	38	0.009	-1	13
2. E*	0.003	-2	1	0.002	-2	0	0.001	-3	-1
3. S*	0.002	-7	-5	0.001	-7	-5	0.001	-7	-6
4. W*	0.010	4	16	0.008	3	15	0.000	-4	-3
5. All	0.038	7	60	0.031	1	46	0.013	-13	6
6†. All	0.039	7	57	0.031	2	48	0.011	-15	3

†See footnotes Table 3

**P_r in ton/r.sq.

††C_i and C_t in $/r.sq.

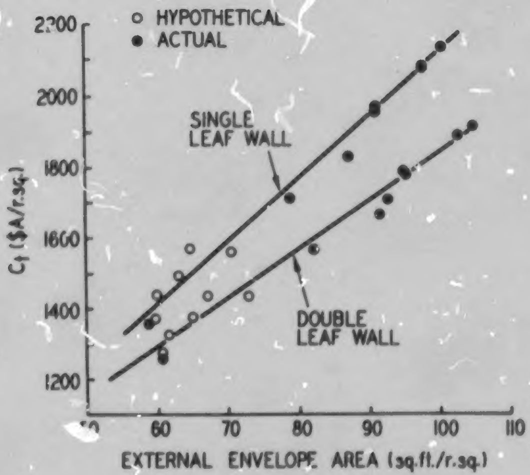

Fig. 1 - Effect of C_t on area of envelope

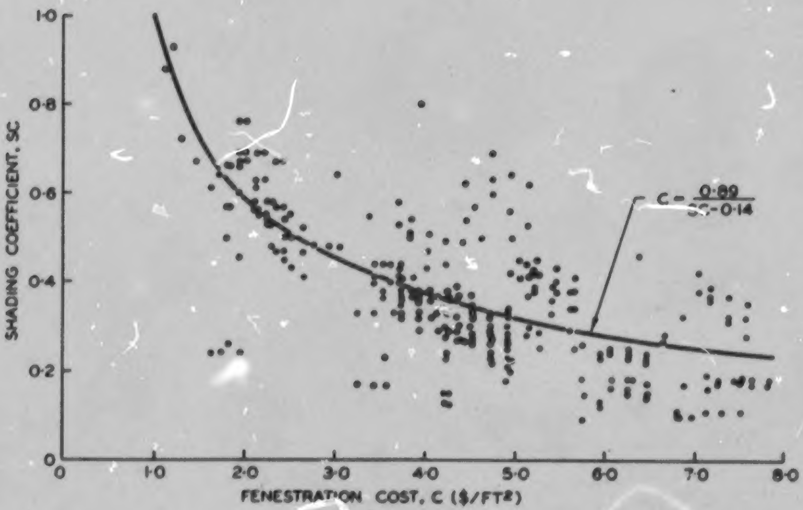

Fig. 2 - Influence of shading coefficient on cost of fenestration

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Use of Modern Computer Programs to Evaluate Dynamic Heat Transfer and Energy Use Processes in Buildings

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Salient features of the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Task Group procedures for calculating heating and cooling load are described. It is stressed that the significance of the thermal storage effect is to be found in the conversion of the heat gain process into the cooling load, even in commercial buildings.

An NBS computer program (NBSLD) was used to augment the ASHRAE methodology. This program was designed to predict the indoor temperature of buildings with limited air conditioning or none at all. Various calculation results obtained by NBSLD are illustrated, some of which are compared with the experimental results.

A simple cooling load calculation illustrated in Chapter 28 of the 1967 ASHRAE Handbook of Fundamentals is used to compare the results obtained by the NBSLD program and the program developed by the U. S. Post Office Department (USPOD), which is an adaptation of the ASHRAE Task Group Procedure.

Les caractéristiques des méthodes de l'"ASHRAE Task Group" pour calculer la charge calorifique et la charge de refroidissement sont décrites. On souligne que la portée de l'effet d'accumulation thermique réside dans la conversion du processus de gain calorifique en la charge de refroidissement, même dans les bâtiment commerciaux.

L'amélioration de la méthodologie ASHRAE afin de pouvoir évaluer la température prévue d'une pièce pour des bâtiments non-climatisés ou mal climatisés est incorporée dans la méthode de calcul développée par le National Bureau of Standards. Les résultats de divers calculs obtenus par NBSLD sont expliqués; certains sont comparés avec les résultats expérimentaux.

Un simple calcul de charge de refroidissement illustré au Chapitre 28 de l'"ASHRAE Handbook of Fundamentals" de 1967 est utilisé pour comparer les résultats du programme USPOD, qui est une adaptation de la méthode ASHRAE et NBSLD.

Key words: ASHRAE Task Group on Energy Requirements; computer application; heating/cooling load; room temperature; thermal environment.

1. Introduction

During the last few years the application of computers for heating and cooling load calculations and for determination of the energy requirements for buildings has increased rapidly. The enthusiastic use of computers for this particular type of environmental engineering problem was amply manifested during the First Symposium on the Use of Computers for Environmental Engineering Related to Buildings. The symposium was sponsored jointly by the National Bureau of Standards (NBS), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and Automated Procedures for Engineering Consultants (APEC). It was held at the National Bureau of Standards on November 30 - December 2, 1970. It drew approximately 400 engineers and architects throughout the world. Among 59 technical papers presented at this symposium, 35 dealt with the subject of heating and cooling load calculations.

Although there are numerous computer programs for heating and cooling load calculations, they vary considerably with respect to the degree of sophistication. The diversity of the program is noticeably wider for the cooling load calculation than for the heating load. The cooling load calculation is more complicated than the heating load because the dynamic interplay among building construction, internal heat generation, heating and cooling systems and outdoor environment, especially solar radiation and humidity, must be taken into consideration. Unlike the conventional steady state type calculations dealing with the overall heat transfer coefficient (U values) and the temperature difference between outdoor and indoor conditions (Δt), which are used for the design heating load calculation, the influence of solar radiation is so large for the cooling load calculation that more elaborate procedures are needed. Until recently the treatment of the dynamic aspect of the cooling load calculation was not well formulated for most of the computer programs. Most of the calculation methods were then designed to provide quick results to assist manufacturers or installers of the heating and cooling units. Little information was available to predict actual performance of the heating and cooling system as installed in a given building under dynamic conditions. Yet for the user of the heating and cooling system, it is important to know the operating cost as well as the performance of the system under all weather conditions. Even today, manufacturers' brochures and engineering manuals are incomplete with respect to determining performance at off-design conditions. Hardly recognized was the extent of the energy saving for heating and air conditioning when the room temperature, instead of being maintained constant, is allowed to oscillate slightly in proportion to the change of the load.

It has been claimed that "stream-lining" of the building heat transfer calculation is permissible where the heat gain from the exterior surfaces of the building is small. For large commercial buildings the load from the inner core due to the lighting, occupancy and equipment contributes a much larger share of the total load than the heat conducted through the exterior skin of the building. But for many buildings the major importance of the thermal storage effect is not in terms of the conduction heat gain but in terms of the conversion of the "instantaneous heat gain" into the cooling load. In this discussion the instantaneous heat gain is the rate of thermal energy entering the space to be air conditioned at a given time whereas the cooling load is the rate of thermal energy picked up by the room air at the same time. The rate of heat entering into the space to be air conditioned as heat gain does not instantly become the cooling load unless the room interior surface is perfectly adiabatic. Instead, part of the instantaneous heat gain will be absorbed and stored by the room's interior surfaces and later released to the air. This time delay aspect of the conversion from instantaneous heat gain to cooling load is the major thrust of the dynamic thermal analysis.

A good example of this point can be illustrated for a large commercial building when its lights are suddenly turned on at the beginning of the day and turned off at the end of the day. Electric energy supplied to the lights, however, does not immediately become the cooling load as expected. Instead, a large portion of the heat from the lights will be absorbed by the surrounding walls and warm up the walls instead of the air. Consequently, even when all the lights are turned off, the wall thus warmed will continue to release the stored heat to the room air. This situation is illustrated in figure 1 in a dimensionless form.

The factors to convert this lighting power to the cooling load are called "the weighting factors for lighting" [1][1], and will depend upon the type of the structure as well as the type of the lighting fixture. Figure 2 shows the same type of heat gain vs. cooling load relationships for the solar heat gain and conduction heat gain. Although area under the heat gain curve integrated over a day should be equal to that under cooling load curve, the actual energy required by the refrigeration machinery to absorb the cooling load is not necessarily the same. This is because the efficiency of heat rejection to the ambient by the cooling plant depends upon the outdoor ambient condition as well as the magnitude of the heat to be absorbed, both of which depend upon the hourly profiles of the cooling load and weather conditions. Thus, treating the heat gain as the cooling load by ignoring the thermal storage effect of the structure may lead to a large error in energy estimates even for large commercial buildings. Moreover, during mild climate the indoor temperature may be allowed to float over a certain range without mechanical air conditioning or heating, in which case the energy requirement for the heating and cooling may be near zero. On the other hand, cooling may be required even during the heating season for some particular building zones. Very few of the current computer programs have a capability of treating such situations. These examples illustrate why a sophisticated dynamic thermal analysis is needed for energy calculations of large commercial buildings. For the cooling load calculation for a dwelling unit, the dynamic load thermal analysis should play an even more significant role because internal heat gains are smaller.

Recently the ASHRAE Task Group (TG) on Energy Requirements has developed a recommended procedure to determine the dynamic thermal behavior of building structures. The procedure was published in a special ASHRAE Bulletin [1] and contains several subroutines to be used by engineers for developing their own load calculation programs to suit their own need. Engineers can improve or modify the ASHRAE TG recommended load calculation procedures by adding or deleting, if necessary, several routines.

The U. S. Post Office Department developed a heating/cooling load program by assembling ASHRAE TG algorithms around their own sophisticated shadow program [2]. It permits the treatment of buildings of complex shape to evaluate the shadow effect. At the same time the National Bureau of Standards was developing a computer program (NBSLD) to predict room temperature change for buildings with limited air conditioning or none at all. A purpose of this NBS program is to study the indoor environment as a function of the building shell and climatic conditions. NBSLD incorporates ASHRAE subroutines, and includes a routine needed for the room temperature prediction. This room temperature prediction subroutine is called RMTMP and it can be used to convert the instantaneous heat gains to cooling load without resorting to the ASHRAE weighting factors.

Figures 3 and 4 are sample physiological indices calculated using RMTMP and can be used to define the need for air conditioning from the standpoint of indoor comfort and heat stress criteria. The indoor temperature and humidity were first calculated by applying the NBSLD to a non-air conditioned apartment in Jersey City. August, 1952 weather conditions (figure 5) were used for this calculation. Then the physiological indices were determined from this data. The room data used for this sample calculation were as follows:

1. The exposed surface of the room faces west at approximately mid-height of the 130 foot high apartment building. No building shadow was considered and the adjacent rooms were assumed to be at the same temperature as the room under consideration.

2. The exposed wall was constructed with 7 inch thick concrete and 2 inch insulation, and contained a 100 ft^2 glass window (shading coefficient of 0.22 was assumed for the calculation to simulate double pane windows with a white opaque roller shade). The net wall area after subtracting the glass area was 112 ft^2.

3. The floor/ceiling sandwich was made up of 5 1/2 inch concrete, air space, and 1/8" cork ceiling tile. The total area was 550 ft^2 and the ceiling height was assumed to be 8.5 ft.

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[1] Figures in brackets indicate the literature references at end of this paper.

4. The partition walls were 6 inches of concrete and the total area was 586 ft^2.

5. The maximum number of occupants was 2, the maximum equipment load was assumed to be 1/2 watt/ft^2 of floor area, and the maximum lighting load was 3 watt/ft^2 of floor area.

6. The infiltration and natural ventilation rate was assumed to be 1 air change/hour between 6:00 a.m. and 7:00 p.m., and 6 air changes/hr from 7:00 p.m. to 6:00 a.m. This nighttime increase of the air change was contemplated on the basis that the occupant opened the window or used a fan to bring in the night air to cool the interior of the room.

These types of calculations are now being used to generate technical information as a basis for air-conditioning criteria for buildings.

2. Application of the ASHRAE Algorithms to NBS Experimental Building

The Environmental Engineering Section of NBS measured the thermal performance of a single room house constructed of concrete block within a large environmental chamber. The temperature of the environmental chamber was controlled to follow a periodic cycle simulating the diurnal change of sol-air temperature, based on an average of all the exterior surfaces. The indoor temperature (without artificial heating and cooling) responding to this simulated outdoor temperature cycle was measured under three different conditions; no insulation; 2" insulation (polystyrene foam) on the inside surfaces, and the same insulation on the outside surfaces of the building. Some of the results of these tests are shown together with the computed temperatures in figures 6 through 8. The computed temperatures indicated in these figures were obtained for the observed outside air temperature shown superimposed on each respective figure. It is interesting to note that the indoor temperature fluctuation is smaller for the condition when the insulation was placed outside of the house when equipped with windows than for an earlier condition when the insulation was placed inside of the house. It is significant that these situations were very accurately predicted by NBSLD.

In other tests with the same building, the required energy input was measured while maintaining constant indoor temperature and with the outdoor temperature going through a similar cyclic condition as before. Figure 9 shows the calculated heating load and the measured hourly profiles of the heating energy rate to the convector type electric heaters installed inside the test building. The agreement between the calculated and observed heating energy rate was considered to be excellent.

The National Bureau of Standards is currently planning additional tests for one of the HUD Operation Breakthrough Housing Systems. A test dwelling unit will first be placed inside the environmental chamber to obtain basic information under controlled environmental conditions and may later be moved outdoors and tested under real conditions. This will provide a further comparison between calculated and measured energy requirements for heating and cooling the building under a wide variety of real weather conditions.

3. Pull-Down Test of a Trailer

The ASHRAE computational method can be applied to its best advantage to the transient heat conduction problems. Shown in figure 10 is a result of a "pull-down" test conducted on a refrigerated trailer. The appropriate thermal and physical properties of the truck trailer and the performance data for the refrigeration system were fed into the NBSLD. The observed and calculated temperature during the pull-down period was very similar. This type of program should also be useful for the design and performance evaluation of cold storage warehouses.

4. Comparison of USPOD Program with NBS Program

As indicated earlier, the NBSLD program incorporates many more features compared with the procedure recommended by the ASHRAE Task Group. The major difference is that NBSLD provides an exact heat transfer calculation of indoor thermal environments compared to the approximate ASHRAE weighting factors. In order to compare the NBS program with the ASHRAE procedure, the NBSLD and USPOD programs (the latter a faithful adaptation of the ASHRAE Weighting Factor Procedure) were applied to the calculation of cooling load for an office building illustrated in the 1967 ASHRAE Handbook of Fundamentals [3]. Figure 11 shows that the hourly profiles determined by these two programs are in good agreement. Also indicated in the same figure is the design load given in the 1967 ASHRAE Handbook example, which uses a time averaging technique for converting the instantaneous heat gain into the cooling load. This comparison shows that for this particular construction, the existing ASHRAE Handbook method, the USPOD program and NBSLD provide good agreement of the maximum cooling load. It is not certain, however, whether such good agreement can be realized for very heavy or very lightweight constructions.

5. Summary

The computer calculation methodology recommended by the ASHRAE Task Group was discussed in relation to the conversion of cooling load from the instantaneous heat gain. As an extension of the ASHRAE Task Group method, a computer program called NBSLD was developed at the National Bureau of Standards. A unique feature of NBSLD is its capability for obtaining the temperature of the room air when the building is not air conditioned. This feature is useful in evaluating the need for air conditioning during the intermediate seasons, or in determining the need for air conditioning of a particular building in a given climatic zone. It is pointed out that NBSLD also permits an accurate evaluation of the cooling load calculation when the room air temperature is prescribed instead of being predicted.

6. References

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[2] GARD/GATX, "Computer Program for Analysis of Energy Utilization in Postal Facilities", U. S. Post Office Department Publication, 1970.

[3] ASHRAE Handbook of Fundamentals, ASHRAE publication, p. 506, 1967.

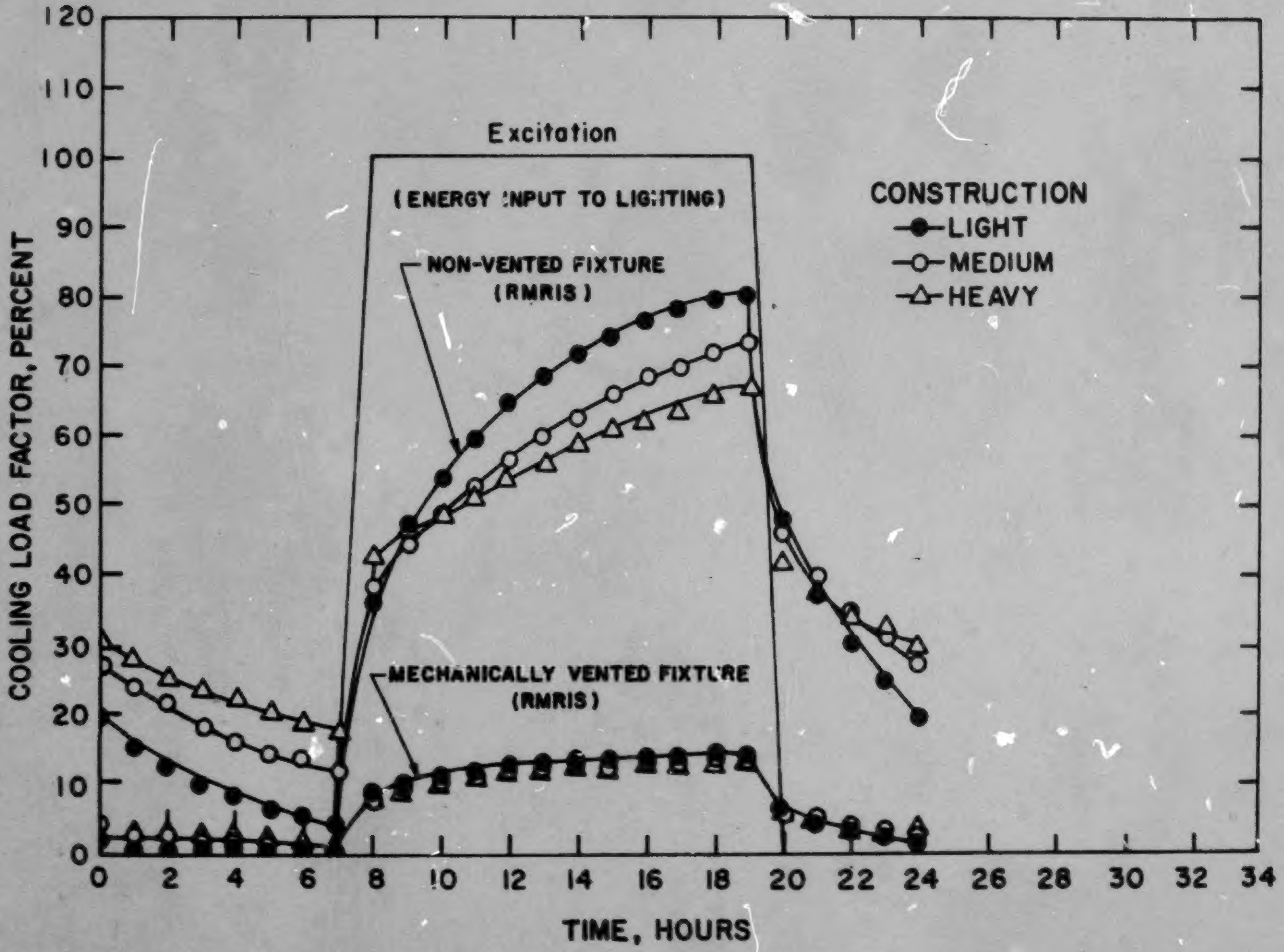

Figure 1 Cooling load factors for use with electric energy input to lighting fixtures

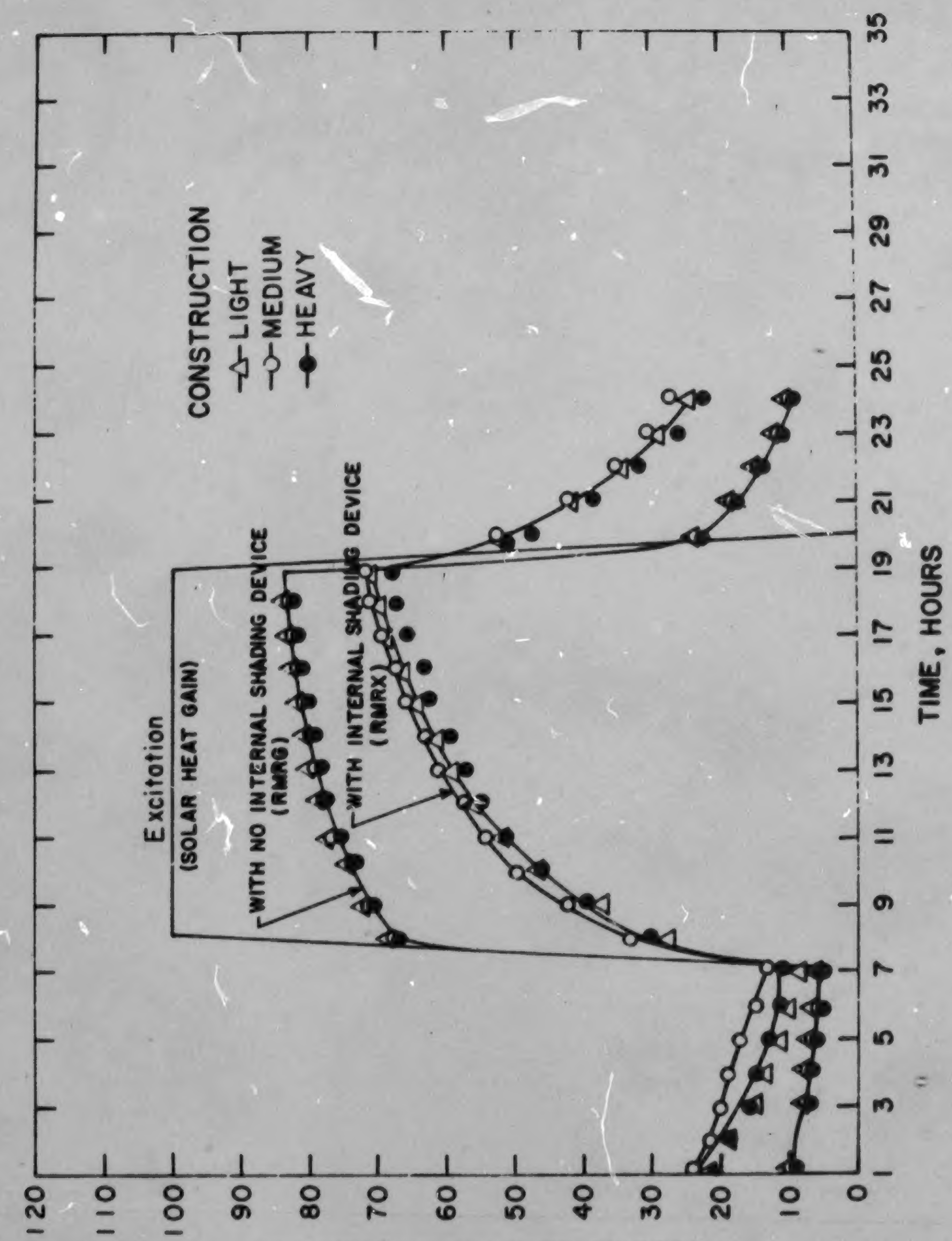

Figure 2 Cooling load factors for solar heat gains

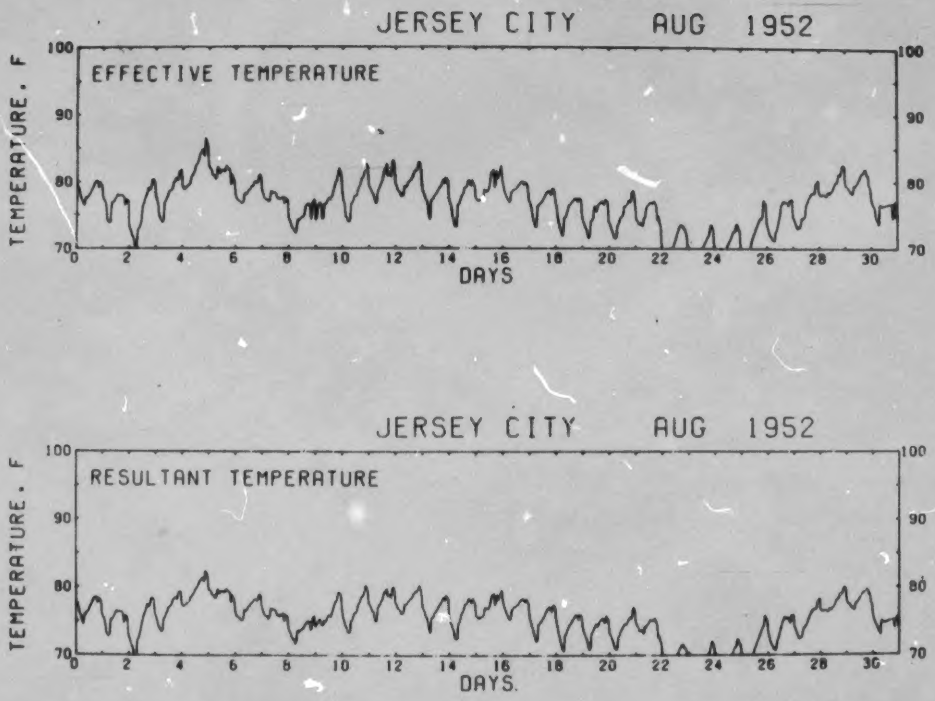

Figure 3 Comfort indices as determined by the use of NBS computer program to predict indoor temperature and humidity

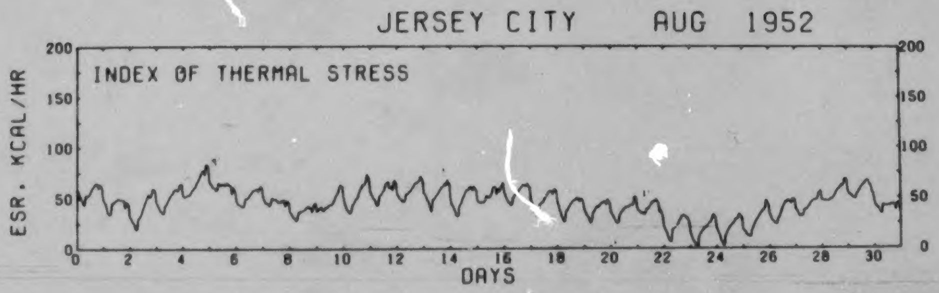

Figure 4 Heat stress index as determined by the use of NBS computer program to predict indoor temperature and humidity

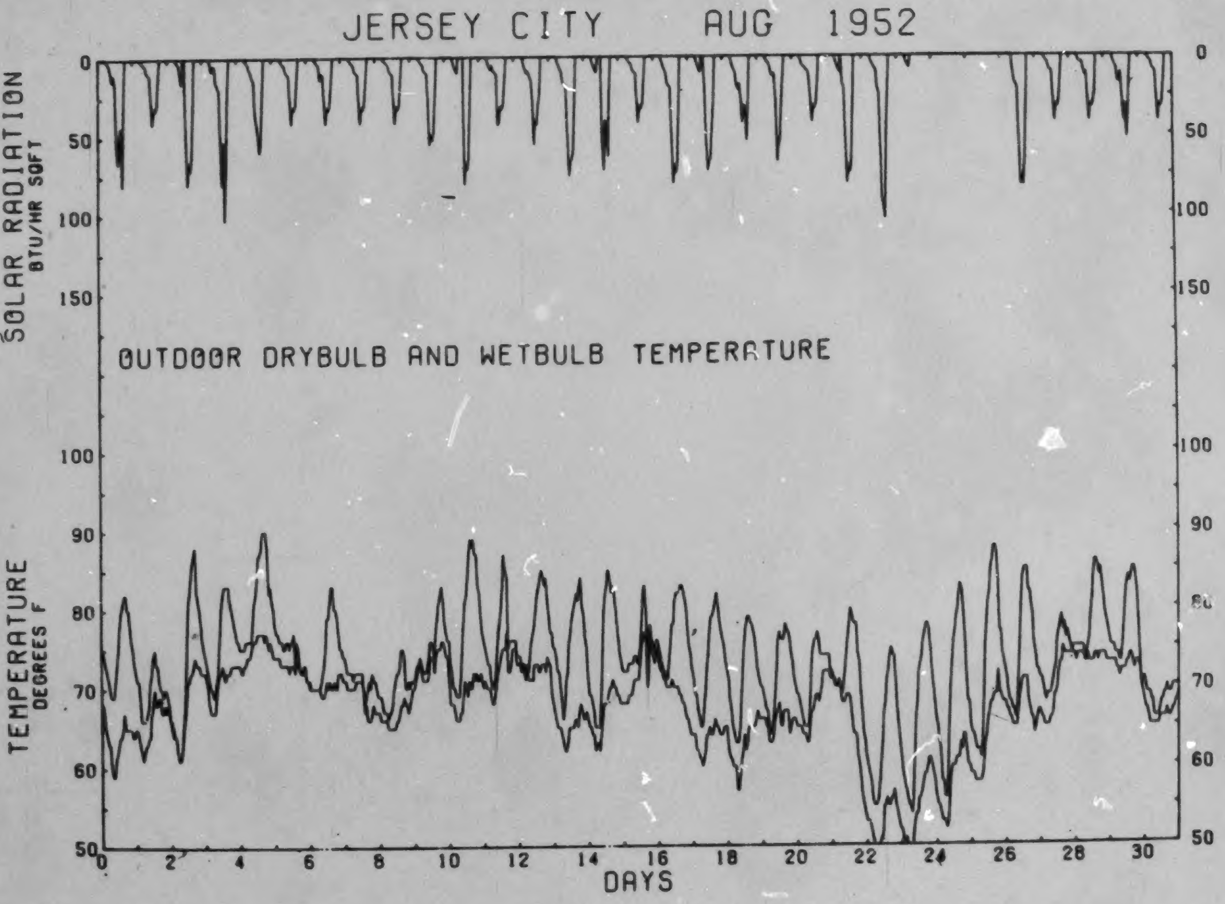

Figure 5 Weather data used by the NBS computer program for the calculation of figures 3 and 4

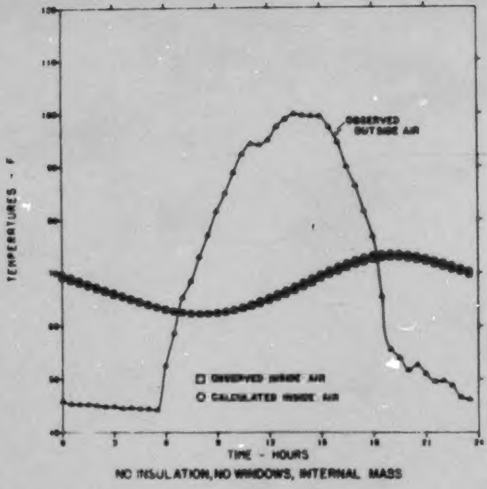

Figure 6

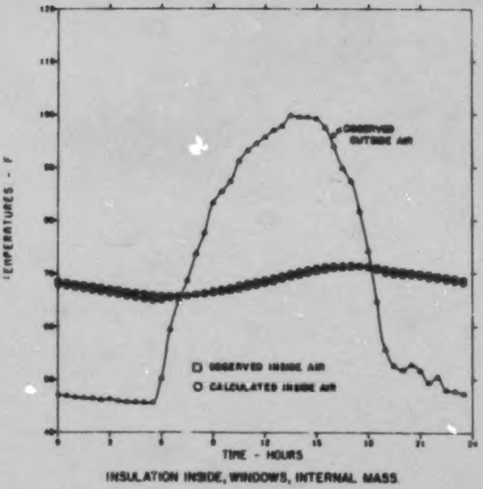

Figure 7

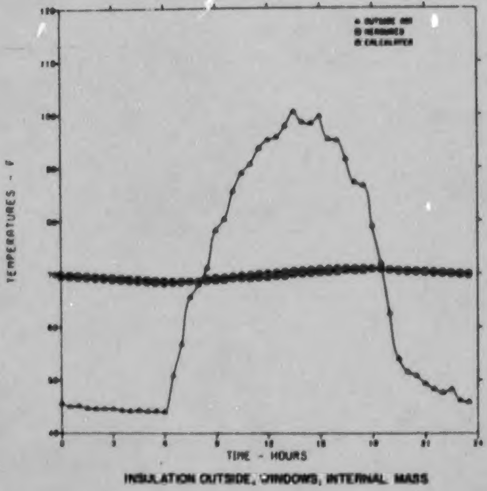

Figure 8

Figure 6-8 Comparison of predicted and observed indoor temperature on an NBS experimental house

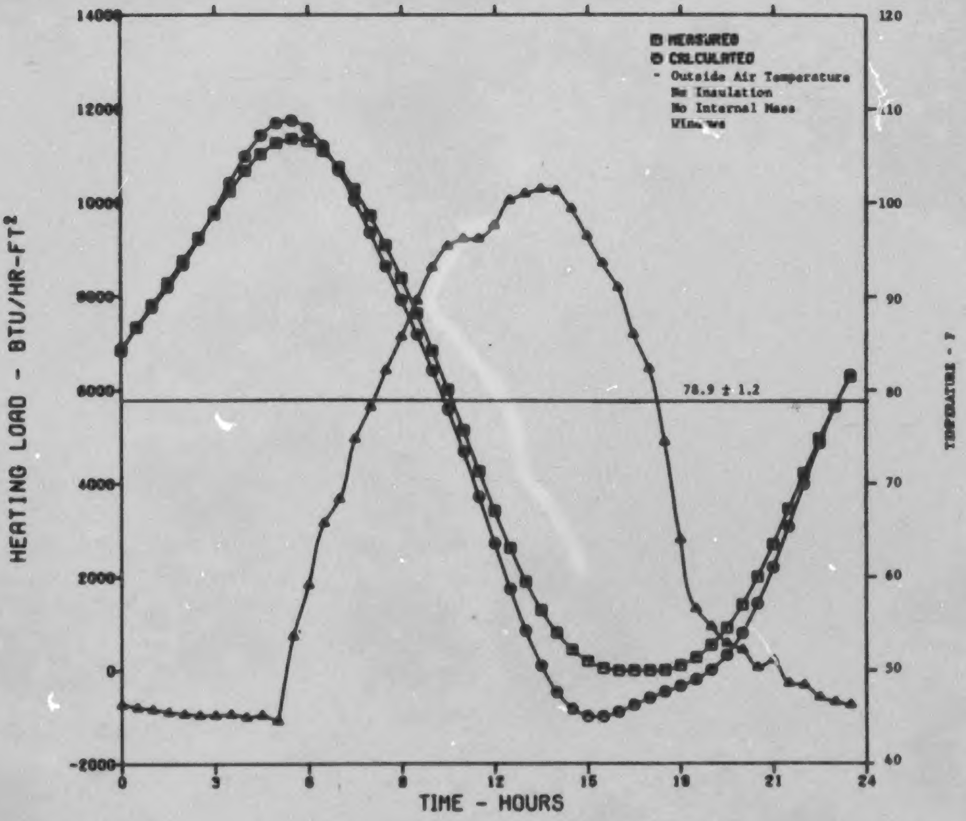

Figure 9 Comparison of predicted and observed energy requirement on an NBS experimental house

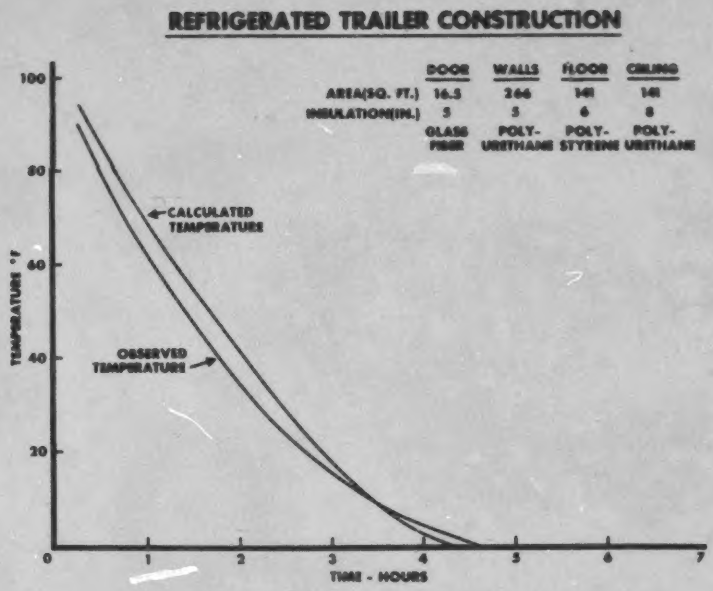

Figure 10 Comparison of predicted and observed air temperature inside a trailer-truck

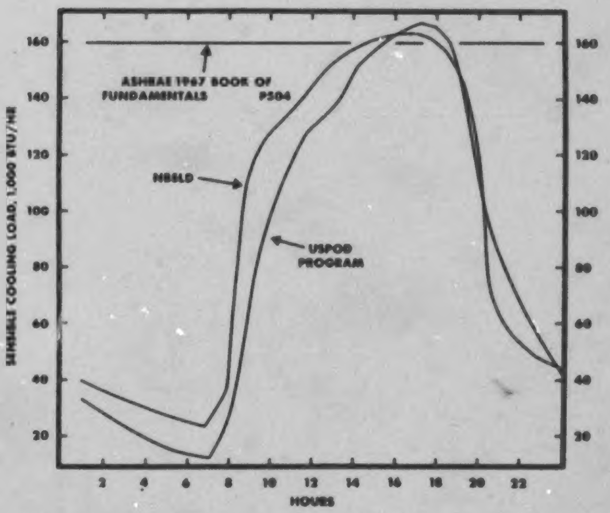

Figure 11 Comparison of cooling loads calculated by the NBS program, the USPOD program and the ASHRAE method for the example given in 1967 ASHRAE Handbook of Fundamentals

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

The Application of Total Energy Systems to Housing Developments

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A pilot investigation of the performance of a total energy system was undertaken by the National Bureau of Standards to evaluate the potential for decreasing the amount of fuel required to provide the utility services to an apartment complex of 500 units and for better control of noise and air pollution. This installation is being made at a site in Jersey City as a part of the BREAKTHROUGH program of the Department of Housing and Urban Development. The selection of the site followed a feasibility study of eleven sites distributed over the United States and the preparation of a performance specification which set forth the design conditions, the requirements for reliability, stability and safety of the system and the environmental quality that must be attained.

The pilot total energy plant is being extensively instrumented to determine its thermal efficiency; the daily and seasonal load patterns; the reliability of the utility services; the level of noise and pollution control; the maintenance and repair requirements; the owning and operating costs; and the occupant response to his environment.

Le Bureau National de Standards a entrepris une expérience-pilote de la performance d'un système d'énergie totale pour évaluer son potentiel de réduction de la quantité de combustible requise par les services communs d'un ensemble de 500 unités d'habitation, et pour un meilleur contrôle du bruit et de la pollution. On a choisi un site de New Jersey, dans le cadre du programme BREAKTHROUGH du HUD (Département du Développement du Logement et de l'Urbanisme). La sélection du site a suivi une étude des possibilités de 11 sites répartis dans tous les Etats-Unis et la préparation de spécifications de performance qui ont fixé les conditions d'étude du projet, les exigences de fiabilité, de stabilité et de sécurité du système, et la qualité de l'environnement qui doit être atteinte.

L'installation-pilote d'énergie totale est expérimentée largement afin de déterminer son rendement thermique, les courbes journalières et saisonnières de charges, la fiabilité des services communs, le niveau du contrôle du bruit et de la pollution, les exigences d'entretien et de réparation, et les réponses des occupants à leur milieu.

Key words: Energy conservation in housing; energy systems for housing; environmental quality in housing; field study of energy systems; total energy systems; utility system performance.

1. Introduction

Concurrent with the national effort to accelerate the construction of housing in the United States, much attention has been drawn to the continued availability of some forms of energy and to the effects of energy use on environmental quality.

The responsibility of the Department of Housing and Urban Development for improving present urban areas and those yet to be built requires that attention be given to the efficient utilization of the energy resources of the country. Efficient use of energy in housing is important because residential and commercial use of energy accounts for about one-third of the total U. S. consumption. The foregoing considerations have led the Department of HUD to initiate a pilot program on the application of a total energy system to a selected part of the BREAKTHROUGH housing program. This program is a part of a broader program on utilities research being carried out by the Utilities Technology Division in the Office of the Assistant Secretary for Research and Technology of that Department.

The objective of this research on energy systems is to promote the efficient use of energy in various forms to the current and future population needs with a minimum adverse environmental and ecological impact. The program does not seek to develop component technology.

The generally accepted industry definition of a total energy system for commercial or residential applications is a system that uses a prime mover for on-site generation of electricity and recovers waste heat from the prime mover for space heating and cooling and domestic hot water heating. The principal loads on a total energy system in a residential application are: electricity for lighting, motors, and appliances; space heating; space cooling; and domestic hot water heating. If there is community development, such as retail stores, schools, and recreational centers, associated with the site, there will be other types of loads on the system.

Under favorable conditions the electric energy requirements and the uses of the waste heat of a given installation are such that the total amount of fuel energy utilized by the total energy system is less than would occur if electric energy was taken from a central utility system and the other energy requirements were supplied by fuel-burning equipment at the site. To the extent that this favorable balance of loads occurs, there is good potential for lowering fuel costs and, in some cases, overall annual cost for energy by utilizing a total energy system. Although there are several hundred total energy installations [1] [1] in the United States, less than fifty of these serve housing developments.

Total energy systems can be designed to utilize almost any energy source. Internal or external combustion engines or turbines can be used for driving electric generators and air conditioning compressors, which may be of either the reciprocating or centrifugal type. Absorption water chillers can be used to provide air conditioning. Space heating and cooling and domestic water heating can be accomplished in a variety of ways, with the electric and heat energy being supplied from the central plant. Total energy systems in the United States most often use gas reciprocating engines as prime movers for electric generation, absorption chillers for air conditioning, and steam or hot water for the primary heating fluid.

A pilot field study of a total energy system utilizing a BREAKTHROUGH housing development site, was designed to develop the following information:

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[1] Numbers in brackets indicate references at end of text.

(a) The daily, weekly, seasonal and annual load patterns for energy use on the site.

(b) The thermal efficiency of the plant.

(c) The stability and reliability of the utility services.

(d) The pattern of diffusion of contaminating effluents.

(e) Degree of noise control attained.

(f) Occupant response to the environment.

(g) Maintenance and repair requirements.

(h) Owning and operating costs.

(i) Characteristics of selected innovative plant components.

2. Feasibility Study of Alternate Sites

A feasibility study for the application of a total energy system was made for the eleven sites selected originally by the Department of Housing and Urban Development for installation of BREAKTHROUGH housing. Past experience with the application of total energy systems to apartment complexes indicated that an acceptable load factor depended significantly on the need for both space heating and space cooling. Furthermore, some minimum number and density of dwelling units on a site are needed to attain acceptable levels of capital investment and distribution costs per dwelling unit. The two sites at Seattle and those at Houston, Kalamazoo and Wilmington were eliminated in a preliminary selection based mainly on the foregoing considerations.

A more detailed study was made of the remaining six sites at Indianapolis, Jersey City, Macon, Memphis, Sacramento, and St. Louis. These sites ranged in size from 6 to 50 acres[a] and would accommodate from 300 to 500 dwelling units each. The corresponding density ranged from six to eighty dwelling units per acre. From 0 to 60 percent of the units were to be incorporated in high-rise structures.

Many different parameters were determined to have some bearing on the suitability of the six sites for a total energy system. The parameters of a technical nature were: the number of dwelling units and their density and arrangement; the summer and winter degree-days and winter design temperature; and the method of construction and assembly of the housing systems. The administrative considerations were: the number of different housing systems to be built on the site; the anticipated level of reserve electric-generating capacity available; the amount of community development to be provided; the time schedule for beginning of construction; and the interest of the site planner and developer in total energy systems. The financial parameters were; the relative cost of purchased electrical, gas and oil energy: the first cost difference between the total energy system and a conventional system; and the cost of maintenance and repair.

Calculations were made of the expected loads for space heating and cooling, for domestic water heating, and for electrical uses at each of the six BREAKTHROUGH sites. The calculations of heating and cooling loads and energy requirements were based on published weather data and on the specified maximum heat transmission factors and allowable window areas contained in the BREAKTHROUGH Guide Criteria since the building designers had not yet developed detailed plans of the buildings. Annual electricity and domestic hot-water-usage profiles were developed from published information for similar applications [2-5]. Figure 1 is a sample of a calculated 24-hour electric energy-load profile under maximum winter load conditions for the Jersey City site.

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[a] 1 acre = 4048 m^2

A computer program was prepared to calculate the monthly and annual energy and fuel usage and cost for each of the six housing sites identified earlier. In addition, the program calculated the amount of heat obtained from waste heat recovery boilers, the percent utilization of recovery heat and the supplementary heating required. These calculations were made for several alternative energy systems. Three of these were different types of total energy systems, two were all-electric systems, and two were conventional central systems.

Table 1 shows the calculated annual on-site fuel energy requirements for the six sites for total energy systems using all absorption-type water chillers, and compression-type water chillers, and the optimum combination of the two types. Also shown are the on-site and gross fuel energy requirements for conventional systems using all-absorption and all-compression cooling, respectively, and two all-electric systems employing resistance heating in one system and heat pumps for heating and cooling in the other. The following conclusions are indicated by Table 1:

(a) Of the total energy systems, the system using 100% absorption cooling had the highest fuel energy requirement.

(b) A combination of absorption cooling and compression cooling in a total energy system provided the lowest gross energy usage for all the systems analyzed. This combination fell in the range of 60 to 80 percent compression cooling.

(c) The heat-pump system had the lowest energy requirement at the site. The gross energy requirement for the heat pump system was comparable in many cases with that required by a total energy system using compression cooling only or the best combination of compression and absorption cooling.

(d) The conventional system using compression cooling was more economical in gross fuel energy requirements than the total energy system using all-absorption cooling at every site but Jersey City.

(e) The conventional system using all-absorption cooling had a higher gross fuel energy requirement than the resistance heating system at two of the six sites.

Figure 2 shows graphically the energy cost for the various systems for the housing development at Jersey City, involving the use of gas, oil, and commercially purchased electricity. The following conclusions are indicated by Figure 2:

(a) The total energy system using 40% absorption cooling and 60% compression cooling was the most economical combination at Jersey City. This combination would reduce the overall energy cost about 12 percent as compared to a system using 100% absorption cooling at Jersey City. The corresponding energy saving ranged up to 30% at one of the other sites.

(b) The most economical total energy system may save from 20 to 30% of the energy cost of a mixed-utility combination using purchased utilities at Jersey City. The corresponding saving was 60% at one of the six sites.

(c) The energy cost for a heat-pump system is only about 6% higher than for the best of the two mixed-utility combinations at Jersey City.

The analysis of all the significant parameters involved in the feasibility study led to the recommendation of Jersey City as the first choice for a pilot total energy plant, with Memphis, Macon, and St. Louis following in decreasing order of preference. Although Jersey City did not have the most favorable ratio in the relative costs of gas or oil to electricity of the six sites, it did have the following favorable features: (a) highest total number and density of dwelling units; (b) a large percentage of dwellings in high-rise construction; (c) largest commercial development; and (d) the greatest interest in a total energy plant on the part of the planners and developers. Jersey City was selected for the pilot installation.

3. Performance Specification

A performance specification was prepared for a total energy system supplying an apartment complex. Unique in concept, this specification did not identify the types and sizes of equipment to be furnished, but did specify the load conditions for which the system must be designed; the reliability, stability, and safety requirements of the system; and the environmental quality required for the site.

The specifications set forth the methods to be used in calculating the design space heating and cooling loads; for determining maximum demands and average usage of domestic hot water; and for determining the daily and seasonal electrical energy use profile. The specification provided criteria for determining the amount of standby generating equipment and other replicate equipment needed.

The reliability of the energy services was described in terms of continuity of service, automation, and monitoring and alarm systems.

The requirements for fuel storage reserves and emergency outside power connections were also specified.

The stability of the electrical service was described in terms of voltage and frequency control, long-term frequency correction, and the division of the electric load among operating generators.

Limitations were placed on the air-borne noise transmission to any dwelling unit on the site, to adjacent boundaries of the site, and to any regularly occupied outdoor area. Noise limitations inside the plant were also specified to protect the safety and health of personnel and to facilitate effective communication in critical areas. Vibration isolation of rotating and reciprocating mechanical components was required to limit the vibration transmitted to occupied spaces and to provide for reliable operation and adequate durability of plant components.

Air pollution by combustion gases was limited to the permissible levels likely to be put into effect by 1975, including limits on the discharge of carbon monoxide and nitrogen oxides by the prime movers. The permissible diffusion pattern of the plant effluents, in relation to adjacent dwelling units, outdoor recreation areas, and traffic thoroughfares, was described. Performance guidelines were described for thermal environment, illumination requirements, and suppression of magnetic interference.

Safety requirements for prevention of explosions, fires, floods, and injury to operating personnel, as well as prevention of equipment failure, were set forth in terms of published codes and standards.

Procedures for review of plans and specifications, manufacturers' tests and certification, and site inspection and acceptance tests were included in the performance specification.

4. Plant Design and Equipment Selection

An experienced engineering firm was employed to carry out the actual design of the total energy system. The principal pieces of major equipment selected for the plant are as follows:

(a) Five 600-kW engine-generators using diesel fuel; generation and distribution voltage, 480 volts, 3-phase.

(b) One 790 MBh[3] waste-heat-recovery boiler on each engine-generator.

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[3] MBh = thousand Btu/hr. 1 MBh = 0.293 kW

(c) Two 400-hp[4] hot-water boilers.

(d) Two 546-ton[5] absorption chillers.

(e) Two 16 000 MBh heat exchangers for space heating.

(f) Two 7 000 MBh dry (water-to-air) coolers and one 6 800 MBh emergency heat exchanger for waste-heat disposal.

(g) Separate chilled-water and heating-water distribution circuits to all buildings.

(h) Operating and spare water-circulating pumps.

(i) Four 20 000-gallon[6] fuel-oil storage tanks.

The limited reserves of gas in Jersey City caused the total energy plant to be designed for diesel fuel, for electric cooking in all apartments, and for heating of domestic hot water from the central plant.

Total energy plants for apartment complexes frequently use four engine-generators sized so three units can carry the maximum electrical load on the system while one unit serves as a standby. Since this arrangement does not provide for any standby during maintenance or overhaul periods for any one of the regularly used engines, it was necessary to install five engine-generators in this pilot plant to meet the performance requirements of the specification.

The designer chose hot water as the heat-transfer medium primarily to provide more positive engine-jacket cooling and to facilitate modulation of the system in response to changing loads, although a great many total energy plants use steam as the heat-transfer medium. Hot water at a maximum temperature of 200°F (93.3°C) and chilled water at a temperature of 45°F (7.2°C) will be furnished to the site in separate circuits as required by occupant needs and by the weather. Simultaneous space heating and cooling is optional with the building designers.

5. Field Testing of Total Energy System

Only a limited amount of data has been published on the load profiles and the diversity of energy use in apartment complexes of a few hundred dwelling units. Even less information is available on the reliability and stability of the utility services provided by total energy systems and on the magnitude of owning and operating costs and maintenance requirements. The growing need for economical use of energy and for the control of environmental contamination make a field study of a total energy system very timely. The beginning of construction of the total energy plant at Jersey City is scheduled for latter part of 1971, and full-scale operation is expected about mid-year in 1972. The planned field study is comprised of several major subdivisions as described in the following summary:

5.1 Energy Use Study

Continuous measurement will be made for a year or more of the fuel used, electrical energy generated, heat generated, excess heat discarded, and utilization of electrical energy

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[4] 1 boiler hp = 9.804 kW

[5] 1 ton = 3516.9 joules/sec

[6] 1 gallon = 3.785 liters

and heat energy by all major segments of the load. Electrical energy will be measured at all major points of utilization including (a) the amount distributed to the site; (b) the portion used by each building; (c) the commercial areas and schools; (d) the plant auxiliaries; and (e) the central solid-waste collection system.

The heat energy from the primary hot water system used in the absorption chillers, in the secondary hot water heat exchangers, and that discarded through the water-to-air coolers will be measured continuously. The energy transfer by the chilled water and the secondary hot water delivered by the plant and in the individual buildings will be determined. The utilization of the heat transferred in the engine-oil coolers will be evaluated.

Heat and energy transfer rates in all water and fuel circuits will be determined by flowmeters and temperature sensors as indicated in Figure 3. These data and the electric energy use will be scanned every five minutes and logged on magnetic tape for future processing in the NBS computer.

5.2 Performance of Major Plant Components

The thermal efficiency of the engine-generators, the heat recovery boilers, the absorption chillers, and the supplementary boilers will be determined at various load levels by observations when appropriate load conditions exist. Fuel or energy input and output rates and the corresponding temperatures, pressures, speeds, and other operating parameters will be determined.

5.3 Stability of Electrical Service

Recordings will be made of transient conditions of voltage, frequency, current, power factor, and load division during sudden load changes on the system, during load-dumping conditions when overloads occur, and during the regular sequence of adding an engine-generator on the line or disconnecting one from service. Most of these data can be obtained during scheduled observation periods or during emergency periods of short duration and will not be continuously logged.

5.4 Reliability of Services

Detailed records will be made of the interruptions of electrical service of heating or cooling service due to overload or malfunction of equipment, including a record of the functioning of all alarms and protective devices in the engine-generators, chillers, and boilers. These data will be collected during emergency situations by a separate paper-tape logger when load dumping occurs and when signals are generated by safety and protective devices. These operating data together with documented maintenance and repair requirements will constitute a record of reliability of the various principal mechanical components of the plant.

5.5 Environmental Conditions at the Total Energy Plant

This study will comprise batch collections of information on noise, combustion effluents, air pollution, cooling tower effluents, thermal conditions, and other environmental data for comparison with the requirements of the performance specification.

Typical noise levels at the Jersey City site due to various city activities were measured before construction of the housing was started. After occupancy, noise levels will be determined at the dwelling units nearest to the total energy plant, in outdoor recreational areas, and at the property lines adjacent to the total energy plant to evaluate the effect of plant operation on the acoustic environment. Noise and vibration measurements will also be made inside the plant.

The principal contaminants in the combustion gases from the boilers and engines will be measured for comparison with the requirements of existing standards, and the diffusion pattern of all plant effluents will be determined for their potential impingement on occupied locations in relation to wind velocity and direction.

Illumination levels, thermal environment, and ventilation around major pieces of plant equipment and controls are to be observed and recorded.

5.6 Dwelling Unit Environment

A 2- to 5- percent sample of dwelling units characterized by some of the principal parameters of size, height above ground, exposure and orientation, and building design, will be chosen for measurement of indoor thermal conditions, air infiltration, indoor and outdoor noise levels, indoor and outdoor pollution levels, vibration, and other environmental factors. These studies will be carried out during the cold weather, hot weather, and mild weather seasons of the year. Measurements of the use of chilled and hot water and electrical energy will also be made in these dwelling units, if practical.

5.7 Owning and Operating Costs

A complete record of owning and operating costs for the total energy plant will be kept including investment cost, financing costs and fees, fuel costs, costs for scheduled maintenance and overhaul, and for breakdown maintenance, costs for repair parts and inventory, plant operation and management, taxes, depreciation, insurance, and water; and credits for energy supplied to other facilities and for decreases in costs for other services such as solid-waste management. Records of maintenance, repair, and overhaul costs will be kept for a period of three to five years to properly evaluate the effect of the minor and major overhaul of engines on total costs.

6. Use of Results

It is anticipated that the field studies in Jersey City will develop authoritative and useful information on the following aspects of total energy system operation and application:

(a) The thermal efficiency of a combination engine-generator and waste-heat-recovery boiler under a range of load conditions.

(b) The overall thermal efficiency of a total energy plant serving an apartment complex, and limited commercial and school facilities.

(c) The amount of heat energy that must be discarded because of any mismatch of the electrical loads and heat-energy demands.

(d) The stability of the electrical service in terms of steady voltage, frequency, and load division.

(e) The average reliability of electric and heat-energy services and its relation to the amount of standby equipment available.

(f) The nature and frequency of malfunction of diesel engines under continuous heavy duty.

(g) The ability to predict the need for routine maintenance and overhaul based on performance rather than elapsed running time.

(h) The ability to control on a small site the levels of noise, air pollution, vibration, heat, and odor produced by a central utility plant.

(i) The maximum demand and diversity in usage of electric-energy and heat-energy services in apartment buildings of different design.

(j) A detailed record and analysis of all owning and operating costs.

(k) The performance of selected innovative mechanical components under actual operating conditions.

It is believed that most of the results that are developed for this particular site can be reliably extrapolated to larger housing developments elsewhere, to some variations in the types of building usage combined on such sites, and to installations where different fuel and labor prices are in effect. The results are expected to constitute a good technical base for guiding the wider application of total energy plants.

The Department of Housing and Urban Development does not consider that total energy installations, or their extensions to completely integrated utility systems, are in competition with the electric utility industry. Rather, the Jersey City demonstration, and parallel market studies, should provide sufficient data and incentive for the existing utility companies to consider total energy systems as an alternative to increasing generating capacity at central station installations.

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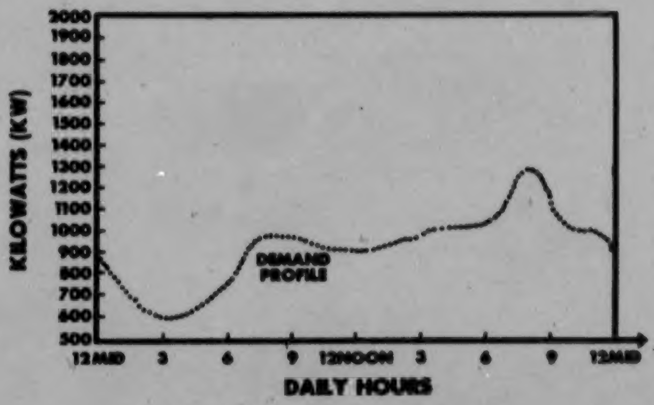

Figure 1 Calculated daily electric energy load profile under maximum conditions for Jersey City (winter)

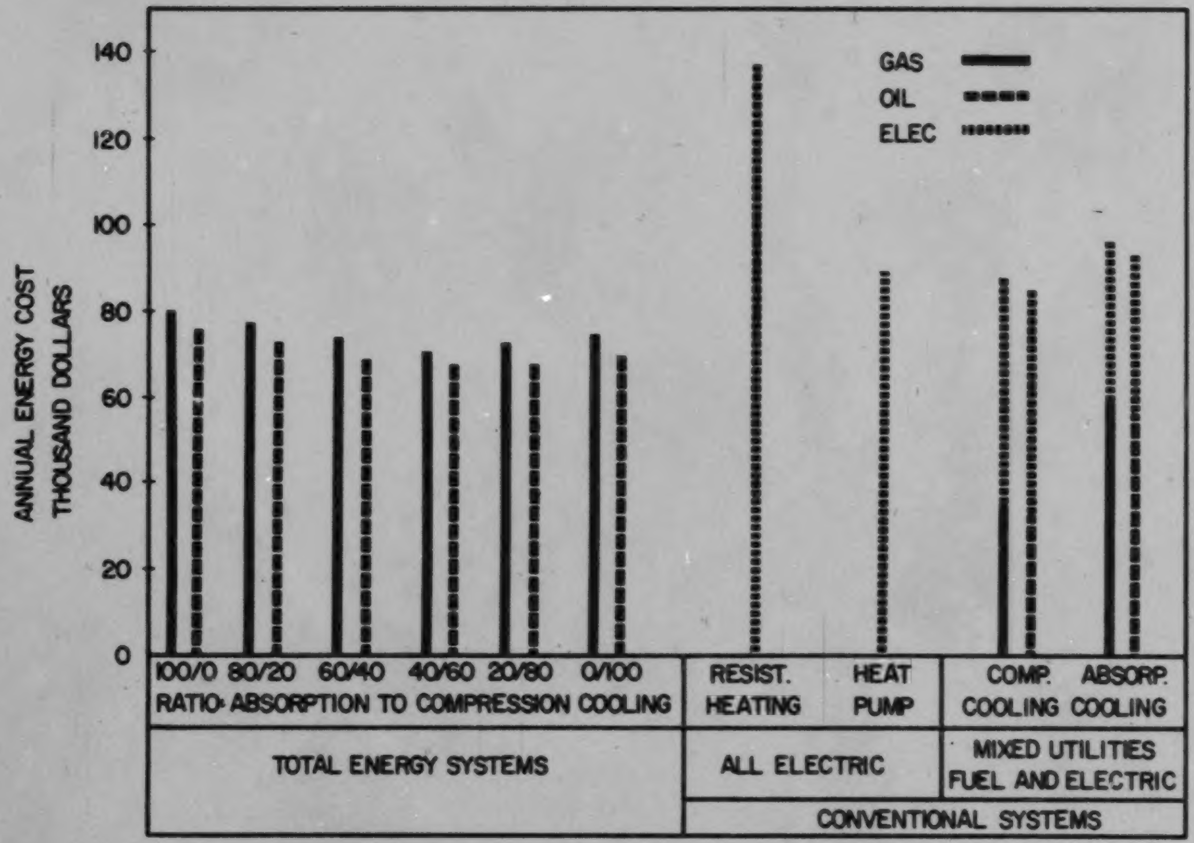

Figure 2 Calculated Annual Energy Cost for Various Energy Systems at Jersey City BREAKTHROUGH Development.

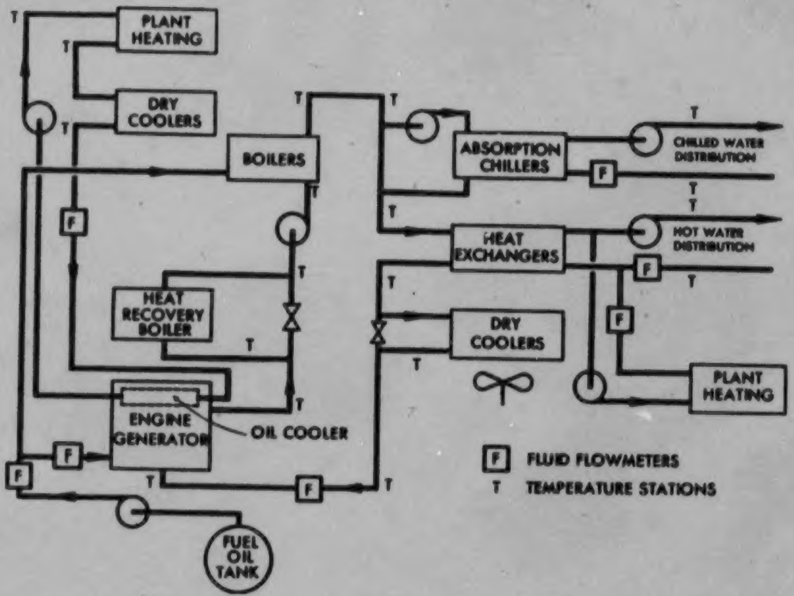
PLANT HEATING
DRY COOLERS
BOILERS
ABSORPTION CHILLERS
CHILLED WATER DISTRIBUTION
HEAT EXCHANGERS
HOT WATER DISTRIBUTION
HEAT RECOVERY BOILER
DRY COOLERS
PLANT HEATING
ENGINE GENERATOR
OIL COOLER
FUEL OIL TANK
F FLUID FLOWMETERS
T TEMPERATURE STATIONS

Figure 3 Partial piping diagram of total energy plant at Jersey City showing location of flowmeters and temperature sensors.

Table 1. Calculated Annual Fuel Energy Requirements for Various Energy Systems BTU x 10^9[7]

Site	Total Energy Systems			All Electric Systems				Conventional Combinations			
	Absorption Cooling	Best Combination	Compression Cooling	Resistance Heating		Heat Pump		Compression Cooling		Absorption Cooling	
	On-Site			On-Site	Gross	On-Site	Gross	On-Site	Gross	On-Site	Gross
Jersey City	90	79	83	45	135	29	87	56	91	79	105
Macon	74	54	58	25	75	18	54	30	59	67	83
Memphis	115	88	94	44	132	30	90	53	99	103	131
Indianapolis	76	63	65	36	108	22	66	46	70	69	85
St. Louis	99	82	86	44	132	29	87	55	93	88	114
Sacramento	72	55	58	28	84	20	60	34	62	64	85

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[7] 10^9 BTU = 0.293 x 10^6 kWh

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A Morphological Performance Evaluation Technique for Moisture Problems in Buildings

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The paper gives a picture of an evaluation technique which may be suitable in solving moisture problems of buildings. The final goal of the procedure is the setting up of the performance requirements which are needed for building elements and products in order to ensure the expected performance of constructions. The evaluation is done with the help of a matrix which is built up as follows: The problem may be divided in the following main factors:

1. Moisture sources
2. Moisture movement and fixation
3. Effects of moisture
4. Performance requirements

Each factor will then be given all the possible values it can get in reality. The main factors form the first vertical column of the matrix, and the possible values of these factors are put on the horizontal lines. The principles and the procedure of the evaluation technique will be discussed. The values of the various "factors" will be introduced, and examples given on the results obtained.

La communication décrit une technique d'évaluation qui pourrait se prêter à la résolution des problèmes d'humidité des bâtiments. Le but de la méthode est de fixer les exigences de performance requises par les éléments de construction et les produits, de façon à assurer la performance "espérée" pour des constructions. L'évaluation est exécutée à l'aide d'une matrice qui est élaborée comme suit: le problème peut être divisé selon les facteurs principaux suivants:

1. Sources d'humidité
2. Mouvement et fixation de l'humidité
3. Effets de l'humidité
4. Exigences de performance

Chaque facteur recevra, alors, toutes les valeurs possibles qu'il prendrait en réalité. Les facteurs principaux forment la première colonne verticale de la matrice et les valeurs possibles de ces facteurs ont été disposés horizontalement. On examine les principes et la méthode d'évaluation. On introduit les valeurs des divers facteurs et on donne des exemples des résultats obtenus.

Key words: Building moisture problems; effects; evaluation; morphological research; movement; sources.

1. General

Defects caused by water and moisture are one of the most difficult problems in building technology. The effects of moisture on the performance of structures and especially on many important properties of building materials are quite significant. It may be generally stated that when the moisture content of materials rises their important properties change for the worse.

In order to be able to predict the behaviour of buildings, building elements and building materials, the moisture content of constructions and materials should be known. This means that the various moisture "sources" should be known both qualitatively and quantitatively. The mechanisms of moisture transfer as well as the properties of materials affecting moisture movements should be clarified. Finally, the effects of a certain moisture content on materials and constructions should be known, in other words, the critical moisture contents of materials in regard to harmful effects of water and moisture. That is how the moisture problems could be evaluated, in the manner of evaluation of structural strength and stability [1][1]. A procedure based on the comparison of moisture sources, moisture movements and fixation,and effects of moisture, makes it possible to evaluate the performance of constructions when they are affected by water or moisture in certain environmental conditions.

The evaluation technique described above may not today be used to give quantitative information on the behaviour on constructions. It is however thought to be useful even now as it enables us to make a systematic survey of the conditions which have an influence on the "moisture performance" of constructions and materials.

2. Principles

An evaluation technique based on the above described principles is under development in connection with a study of performance analysis [2]. The aim of the work is also to provide a basis for a performance-oriented building norm, which deals with moisture problems. This norm is being prepared by a committee appointed by the Union for Civil Engineers in Finland.

The matrix (see appendix) which is the basis of the systematic evaluation technique for moisture problems in building technology has been developed according to the principles of morphological research. The central idea of this method is to clarify all the essential factors which may have an influence on moisture problems as well as the correlation between these factors.

The first step of the formation of the "moisture matrix" is to list all the main factors of the problem. After that the main factors will be divided into smaller units, which could be regarded as parameters of the main factors.

As the factors and their parameters have been listed, the matrix may be set up. The first column consists of the main factors. All possible parameters of the main factors are set up on the horizontal rows of the matrix.

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[1] Figures in brackets indicate the literature references at end of this paper.

The principles in the use of the matrix have been discussed in the paper "Proposed method for prediction of corrosion of reinforcement in concrete" [3]. The procedure when used in moisture problems will be discussed later in this paper.

3. Factors and parameters

3.1. General

The main factors affecting moisture problems in building technology may be divided into the following:

1. Moisture sources
2. Moisture movement and fixation of moisture
3. Effects of moisture (on constructions and materials)
4. Prevention of harmful effects of moisture

3.2. Moisture sources

All the independent phenomena and sources which will bring constructions and materials in contact with water and moisture will be regarded as moisture sources. The moisture sources may further be divided into three main groups.

1. Sources from the outside the building
2. Sources from the inside
3. Moisture from construction (structural moisture)

Sources from the outside consist of environmental moisture and water sources as rain, moisture of air, ground water, etc. The moisture content of the air inside, water and moisture used in different activities, leakages etc., may be included in the sources from the inside. Moisture from construction is the moisture in newly erected constructions when they are completed. The moisture may be due to water used in the preparation of the construction, or from rain during storage, transport and installation etc.

3.3. Moisture movements

Moisture transfer in materials may occur in the form of water or water vapour.

Moisture transfer as water vapour may be due to effusion, diffusion, thermo-diffusion, convection, etc. Water may be transferred by capillary, thermal, osmotic, and thermo-osmotic forces, as well as by pressure differences and gravitation.

The complexity of moisture transfer and the lack of knowledge of material properties in regard to different forms of moisture transfer make it difficult to evaluate exactly the amount of moisture transfer in constructions.

3.4. Fixation of moisture

The moisture of materials may be structural. The moisture may be adsorbed on the surfaces of the pores of the material. Capillary forces may bind water as well as osmotic forces. The pore volume is often not completely filled by absorbed or capillary water, there is still space for free water, which can be easily removed from materials.

3.5. Effects of moisture

Moisture may affect constructions and materials in many different ways. Quite often the effect of moisture is harmful to the object. Moisture may destroy the important properties of materials such as strength, thermal insulating properties, etc. Moisture may affect durability of materials. The aesthetic performance of materials may also be destroyed by the effects of moisture.

The effects of moisture may be divided at least into the following main groups

- Chemical
- Electrochemical
- Physical
- Biological
- Aesthetic
- Physiological

The effects of moisture determine the "moisture performance" of constructions and materials. They are the same kind of criteria which may be used in the evaluation of the behaviour of constructions and materials. If the limiting values in regard to different effects of moisture on materials could be developed as well as the quantity of moisture sources and moisture movements, it might be possible to evaluate the performance of constructions and materials quite objectively.

3.6. Prevention of harmful effects of moisture

The prevention of harmful effects of moisture may be carried out in many different ways. First, the contact of a moisture source with the construction may be prevented or at least quantitatively decreased. Moisture movements in constructions may be diminished by a special kind of moisture insulation or by proper selection of materials and their position in the construction. One possible way to cope with moisture is by the use of materials which have a resistance against harmful effects of moisture. The main possibilities for avoiding the harmful effects of moisture have been listed in Table 1.

4. Evaluation of moisture problems

The morphological model for moisture problems is in Table 2. The starting point of the examination begins with the moisture sources, which form the first horizontal row. They have been divided into three main groups: moisture from the inside, from the outside, and moisture from construction (see Table 1). The next horizontal row is formed by moisture movements and fixation of moisture. The various forms of these factors have been listed. When the moisture comes in contact with constructions it has a certain influence on them. The various possible effects of moisture form the next horizontal row. The last row is formed by the methods of preventing the harmful effects of moisture.

The morphological evaluation of moisture problems may be carried out as follows. At first one moisture source should be clarified qualitatively and quantitatively. As the next step the various possible ways of moisture movements will be studied. After that the fixation of moisture in materials will be clarified independently for every form of moisture movement of the moisture source in question. As the moisture content of the material has been clarified the effects of moisture will be studied.

When the model for "behaviour" of moisture has been structured it is possible to see if the effect is harmful and if it is, how it can be prevented. There are many possibilities, such as for instance, the prevention of moisture movement into the construction, or the tightness of materials may be improved etc.

When the moisture content of materials as well as the effects of moisture have been clarified it is possible to make conclusions on the desirable actions against harmful effects of moisture as well as on the performance requirements which may be set on constructions and materials for different kinds of environmental conditions.

5. Conclusions

The morphological model for moisture problems can be used when the performance of structures as a whole is considered. The method is not intended to be a magic device which may be used to solve all problems easily. However, this kind of model makes it easier to examine the problem systematically and compels taking all possible factors into consideration. At present the morphological model for moisture problems is a rough draft and only gives the main ideas of the system.

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Table 1. Main factors and their parameters.

- A. Moisture sources
  - 1. Sources from the outside
    - 1.1. Rain
      - Water
      - Snow
    - 1.2. Ground
      - Ground water
      - Water vapour in the ground
    - 1.3. Surface water
    - 1.4. Moisture in the air
    - 1.5. Leakages
    - 1.6. Fire extinguishing water
    - 1.7. Water courses
  - 2. Sources from the inside
    - 2.1. Air indoors
    - 2.2. Activities
      - Food preparation
      - Cooking
      - Washing
      - Bathing etc.
    - 2.3. People, animals, plants, food etc.
    - 2.4. Humid rooms
      - Bathroom
      - Laundry etc.
    - 2.5. Leakages
    - 2.6. Fire extinguishing water
  - 3. Moisture from construction
    - 3.1. Manufacturing
    - 3.2. Curing
    - 3.3. Rain
    - 3.4. Air
    - 3.5. Other
- B. Moisture movement
  - 1. As water vapour
    - Effusion
    - Diffusion
    - Thermo-diffusion
    - Convection
  - 2. As water
    - Capillary movement
    - Thermal "
    - Osmosis "
    - Thermo-osmosis
    - Convection
    - Caused by pressure differences
    - Caused by gravitation

(continued)

C. Moisture fixation
   1. Structural
   2. Adsorption
   3. Capillary condensation
   4. Osmotic
   5. Free water

D. Effects of moisture
   1. Chemical
      - *Corrosion*
      - Prevention of hardening
   2. Electrochemical
      - Corrosion of metals
   3. Physical
      - Increasing moisture content
      - Drying
      - Condensation
      - Deformations
      - Frost damages
      - Loosening of surface
      - Efflorescence
      - Cracking
      - Strength properties
   4. Biological
      - Decay
      - Mould
   5. Aesthetic
      - Dirt
      - Change of colour
   6. Physiological
      - Change of climate (indoors)

E. Prevention of harmful effects
   1. Prevention of contact with moisture sources
      - Drainage
      - Form of the building etc.
   2. Prevention of moisture movements
      - Moisture insulation
      - Water insulation
      - Tightening of joints
      - Prevention of air leakages etc.
   3. Leading away the moisture from the construction
      - Drainage
      - Form of the structures etc.
   4. Structural factors
      - Ventilation
      - Position of different layers of the construction
      - Protective layers etc.
   5. Choice of materials
      - Frost resistant materials
      - Corrosion resistant materials etc.
   6. Special arrangements
      - Protective treatment against decay
      - Painting etc.

Table 2. A morphological model for evaluation of moisture problems

Moisture sources	Rain	Ground water	Moisture from the ground	Surface water	Moisture in the air	Leakages	Fire extinguishing water	Water courses
	Moisture in air indoors	Moisture from activities	Leakages	Moisture from construction				
Moisture movements	Diffusion	Convection	Capillary movement	Osmosis	Pressure differences	Gravitation		
Fixation of moisture	Structural water	Adsorption	Capillary condensation	Capillary suction	Free water			
Effects of moisture	Corrosion	Condensation	Deformations	Frost damages	Loosening of surface	Efflorescence	Cracking	Strength properties
	Decay	Mould	Dirt	Change of colours	Change of climate (indoors)			
Prevention of harmful effects	Prevention of the influence of moisture sources	Prevention of moisture movement	Leading away the moisture	Structural factors	Choice of materials	Special arrangements		

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Performance Requirements for Plumbing Systems

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To develop performance requirements for plumbing systems, it is necessary to analyse the related human requirements.

Then it is necessary to analyse all the factors affecting the system:

- Those acting on the installation as a result of human use
- Those acting on the installation as a result of its environment (climate, constructions etc.)
- Those resulting from the effect of installation on the environment

to develop a list of parameters characterizing the performance requirements.

The paper intends to express qualitative requirements and whenever possible define them by evaluation methods giving quantified values.

Requirements related to erection, transportation etc., will not be discussed. The discussion will be limited to performance requirements for dwellings.

Pour développer des exigences de performance pour les systèmes de tuyauterie il est nécessaire d'analyser les demandes humaines en rapport.

Il est ensuite nécessaire d'analyser tous les facteurs affectant le système:

- Ceux qui agissent sur l'installation à la suite de l'usage humain
- Ceux qui agissent sur l'installation et qui traduisent l'action du milieu (climat, constructions, etc.)
- Ceux qui résultent de l'effet de l'installation sur le milieu

pour développer une liste de paramètres caractérisant les exigences de performance.

Le communication a l'intention d'exprimer des exigences qualitatives et autant que possible de les définir par des méthodes d'évaluation donnant des valeurs quantitatives.

Les exigences relatives à la mise en place, le transport etc. ne seront pas discutées. La discussion se limitera aux exigences de performance pour les habitations.

Key words: Evaluation techniques; performance requirements; plumbing systems.

1. Introduction

The intention of this paper is to specify the performance requirements to meet the users' needs for sanitary installations.

It has been necessary to leave out of the paper detailed information on evaluative techniques which are under development. The author will, however, be happy to supply the information when available.

The sanitary installations, as far as this paper is concerned, consist of the sanitary appliances with the necessary piping for supply of water and discharge of waste water.

The performance requirements of the sanitary installations in a dwelling are directly connected with the use of the installation for:

- personal hygiene
- preparation of food
- cleaning the house and furniture
- spare time activities etc.

The main performance requirements also cope with the natural sources such as:

- rainwater
- ground water
- fire and
- the needs for maintenance and exchange of unserviceable parts.

These are therefore included in such a list of human needs.

The further required performance is the performance necessary to fulfill the function of the installation when subjected to the influencing factors both from the use of the installation and from the environment. These performance requirements are worked out in an additional item.

2. Development of the Performance Requirements and Evaluative Techniques

The development of performance requirements starts with general statements regarding the different functional uses of the installation, and the influences to which the installation will be subjected when meeting the required performance.

The statement of functions is based on knowledge of the activities in which the sanitary installation is involved,and a general knowledge of the type of influences to which the installation will be subjected both from the user and from the environment. The performance required is generally related to the whole plumbing system, and not to already existing devices except when directly specified.

A very simple example of the statement of a performance requirement is: The strength of a child's hand should be sufficient to open the faucet.

The next step would be to develop the necessary performance criteria. Here, in the example, the force necessary to open the faucet would be considered the performance criterion. The ideal situation is when it is possible to define and measure the performance in such a way that it is clear to the user what is a high performance, what is a low performance, and what is acceptable performance under certain circumstances. The required performance for the same sanitary appliance may be very different under different circumstances.

Examples:

1. Variation in water temperature of 5°C is acceptable in a bidet for washing feet but not for washing the seat region.

2. Acceptable flow of water into a kitchen sink of 0,05 l/s is acceptable for flowing into a glass but not into a bucket.

Matrix Giving Activities, Influencing Factors and Related Performance Requirements

In Table 1, an attempt has been made to identify human needs for a plumbing system and to relate these, through use of a matrix to appropriate statements of performance requirements. The matrix has a dual feature which makes it possible to relate the performance requirements to fixtures, appliances, and appurtenances that make up a plumbing system.

In a similar way an attempt has been made in Table 2 to identify the influencing factors and the related performance requirements. The influencing factors are those which the installation will be subjected to from the human use and from the environment.

Each performance requirement has been stated in several general terms defining the purpose of the requirement. Further several criteria have been given for each particular requirement.

A grading from 1 to 6 of the criteria has been proposed for evaluating the performance criteria. It is known that other similar gradings have been used at different institutions. Through this grading it should be possible to state the performance required under different circumstances and to determine whether the stated performance is obtained.

The necessary comment is presented as a guidance for selecting a fitting performance.

Sometimes a high performance regarding one property is necessarily connected with a low performance regarding another property. It may also be the case that different desired properties cannot be obtained at the same time.

Examples of conflicting performance:

1. The temperature of water for dishwashing should be as high as possible for sterilizing but must be low enough to avoid burning the hands.

2. The need for a favourable price might go against a high degree of quality. Small variations in quality can give great variations in price. The price should therefore be given as a function of desirable performance and with possibilities for qualitative choice. Out of this function the most economical installation with the desired quality can be estimated.

Changes in price, as a result of deviation from specified quality of the finished installations, should also be possible to assess when this is agreed upon beforehand.

The performance requirements in connection with transport, fitting, etc. (i.e. before the installations are put into use) will not be dealt with. The performance requirements are mainly meant to cover installations in private dwellings.

4. Example of a performance requirement and evaluation requirement: Avoid bubble noises (Table 2, No.5)

4.1 Performance in General Terms

Air should not be forced through a water-filled part of the waste system, e.g. the trap, in such a way that it might cause bubble noises.

4.1.1 Criterion No. 1

Noise from traps is caused by water flowing through it. Noise from air bubbles going through the trap when the appliance has been in use should be avoided; this is described in the table below.

Avoidance of bubble noises when discharging appliances

Avoidance of bubble noises should be	Bubble noises due to	
	Emptying a basin, measured in % of full height of water level	Water flow, Q, for 10 sec. into appliances which cannot retain any water 1)
1. None	10	Q/2 2)
2. Very little	20	Q 3)
3. Little	40	Q + Q'/2 4)
4. Moderate	60	Q + Q'
5. High	80	1,5(Q + Q')
6. Very high	95	2 (Q + Q')

The requirement does not concern the WC which produces noise during the discharge itself.

1) Q = Full flow of cold water, Q' = Full flow of warm water
2) Devices without hot water Q/3
3) " " " " Q/2
4) " " " " 2Q/3

Evaluation

Appliances with a basin are filled to 10% of their height between the bottom and the rim level. The outlet should be shut at the outlet itself or if it is not to be closed, a special device has to be used. The outlet should be fully opened in one second. The water should run out with a time of flow according to table 1, requirement No. 14, until the appliance is empty. Noise from air bubbles going through the trap should be noticed. When air bubbles do not occur the testing is repeated by raising the water level in the basin to 20, 40, 60, 80 and 95% of the full height.

Appliances which cannot retain any amount of water are tested by tapping water through it for 10 seconds on an ordinary working day between 10 and 14 o'clock. The water flow is then quickly turned off and audible bubble noises are watched for.

Avoidance of noises is graded by providing the following water flow: First cold water with half of the full flow. Secondly, giving full flow of the cold water. Thirdly, full flow of cold water and half flow of hot water. Fourthly, full flow of both hot and cold water (fixtures without hot water are tested the first 3 times with cold water at 1/3, 1/2 and 2/3 flow and the fourth time with a full flow). The two last times the water is turned fully on and then water is added from another source, with at first 50% and finally 100% added. The water flow which gives noise from air bubbles from the trap is registered.

Comment

Air bubbles due to the selfsiphoning caused by discharging of a WC is not considered to be annoying in the WC room. The reason is that the noise of these air bubbles are often weaker than the noise caused by a person while using and emptying the flush tank of the WC.

Requirement and evaluation are not finally tested and justified. See also table 1, performance requirement No. 14, carry off excess water.

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4.1.2 Criterion No. 2

Noise from a trap caused by water flow passing in the stack

Noise from air bubbles passing through the trap caused by the discharging of appliances above, should not be heard. This is expressed in the table below.

Avoidance of bubble noises when discharging other fixtures

Avoidance of bubble noises should be	The probability during a peak load period of simultaneous use of applicances causing no bubble noise
1. None	1
2. Very little	<1 - 0,1
3. Little	<0,1 - 0,01
4. Moderate	<0,01 - 0,005
5. High	<0,005 - 0,001
6. Very high	< 0,001

Evaluation

Siphoning noises through the traps are found when discharging waste water from the appliances above.

Discharging is repeated without adding of water in traps. Bubbles or siphonic noises which can be heard in the room are noticed.

The flow of waste water for the testing should conform with the amount of waste water from the appliance above which has greatest water flow and longest time for discharging into the waste system. The flow of waste water should come from discharging the highest located appliances simultaneously. The number of the fixtures are calculated from the general probability equation:

$$P(x = r) = \binom{n}{r} p^r (1 - p)^{n - r}$$

to find out whether more than a given amount of the installed appliances will be in simultaneous use during a peak load period.

P = requested probability
n = number of installed appliances
r = number of appliances in simultaneous use

$$p = \frac{\text{time for one discharge}}{\text{time between each discharge}}$$

The desired probability is the basis for the calculation. Moderate noise reduction (see last table) gives a probability 0,01 for a number of appliances in simultaneous use during a peak loading period. Calculations based on Wise and Croft (1)[1] (see NBRI report 46 (2), page 17) show a probability less than 0,01 for the following appliances of traditional type in simultaneous use:

Bathtub

Up to 4 bathtubs installed above, 1 discharged at the time
5 - 11 " " " " , 2 " " " "
12 - 20 " " " " , 3 " " " "
21 - 33 " " " " , 4 " " " "
34 - 46 " " " " , 5 " " " "

WC

Up to 20 WC installed above, 1 discharged at the time
21 - 100 " " " , 2 " " " "
101 - 190 " " " , 3 " " " "

Bathtubs and WC's are discharged simultaneously in ordinary dwellings, as it is those appliances which cause the highest flow when they are in use at the same time during a peak loading period.

Kitchen sinks with or without a dishwasher installed on the same waste system. (They are not included in the traditional testing where it is probable that WC and bathtub are used simultaneously).

Up to 8 kitchen sinks installed above, 1 discharged at the time
9 - 28 " " " " , 2 " " " "
29 - 48 " " " " , 3 " " " "

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[1] Figures in brackets indicate the literature references at the end of this paper.

Washing machines, lavatories and bidets follow the same pattern of use as the kitchen sinks.

Shower cabinets follow the same pattern of use as bathtubs when the latter are not installed.

Floor drains with a faucet above and other similar appliances have a pattern of use as for kitchen sinks. Flow from tubs through floor drains is dealt with as a discharge from a bathtub.

Procedure

The influence of the flow from the WC should be the same as usual discharge from the WC pan, according to the following procedure.

12 toilet papers, of size A6 crepe quality, approx. 40 g/m^2, easily creased, are added to the pan in such a way that all the papers if possible touch the water level. Two papers are added every 5 seconds. The discharge will be 5 seconds after the last piece of paper is added. (Based on a proposal for a DIN-norm.)

The flow from a bathtub should start with a water level at about 150 mm from the rim of the tub. When testing a bathtub and the WC together, the discharging of WC should take place in the first 30 seconds of emptying the bathtub.

The flow from a shower should be the full cold water flow.

Kitchen sinks, washing machines or dishwashers connected to waste pipes which do not get any flow from WC and bathtub should be tested together with other types of appliances having basins connected to the waste pipe.

The discharge should always be from the full basin (50 mm below the rim level).

Other types of appliances should be tested singularly.

Comment

Bubble noises coming from air going through a trap are annoying for most people in buildings with a low noise level. Bubble noise can also come from traps which are not in steady use. Bubble noises are one of the design criteria for the diameter of the stack. Smell from sewer gases or even sewage being blown back into room will come at much higher loading of the stack.

At present the Norwegian Building Research Institute is studying which diameter of the stack is necessary in a 8-storey building when the influences vary according to a specified program.

Experience in Norway since the end of 1920 seems to show that certain varieties of 75 mm stacks with a simple ventilation on the top of the stack fulfill the requirement of a moderate avoidance of noises (table on page 4). We therefore assume that there will be no bubble noise when certain constructions for these stacks are used with a probability of 0,01. It is desirable to find useful variations in form and location of the fittings for the drain. This will be the first part of the investigation.

Diameters and angles in the branches on the stack are important for the pressure variations in the trap when suction is caused by the water flow in the stack (induced suction). The relationship between the variation in pressure in the stack and the forcing of air through the trap has to be studied more closely to make it easier just to measure the run of the pressure in the stack and thus make it possible to choose the right details for the stack.

Flow from the WC at the lowest connection can only influence traps higher up on the stack to a slight extent. (NBRI-report 46, (2), page 39). Adding water flow from the WC has,

however, a strong influence on the pressure variations in traps lower down than the WC connection on the stack.
These variations in pressure probably cause bubble noises before other critical diameter influences occur. We will assume that this parameter is critical for the diameter.

Outside air pressure over the ventilation of stack may occur in districts with strong winds, when the vent is positioned on the roof.

Under pressures from these strong winds an increase of pressure variations and siphonation may occur in the stack. It should be possible to act against these variations by placing the ventilation in the most preferable zone of wind pressure.

Indoor mechanical ventilation may act in a similar way as outside wind pressure. As a rule the ventilation causes reduced pressure outside of the appliances. Therefore it will mostly act against the loss of water seal in the traps.

Calculating the probability of simultaneous use

The probability of there being more than 1 WC discharging at the same time out of a total of 20 WC's during a peak load period is less than 0,01.

Calculations show that the probability also is less than 0,01 for more than 2 in simultaneous use of 100 connected WC's during a peak load period.

Calculation (according to the general probability equation):

$P(x = r) = \binom{n}{r} p^{r} (1 - p)^{n - r}$ and $\binom{n}{r} = \frac{n!}{r!(n-r)!}$

$P = 0{,}01$
n = number of appliances, 100
r = " in simultaneous use
$p = \frac{\text{time for one discharge, s}}{\text{time between each discharge, s}} = \frac{5}{1140} = 0{,}0044$

The probability of 2 WC's discharging simultaneously

$P(r = 2) = \binom{100}{2} 0{,}0044^{2} \ (1 - 0{,}0044)^{100-2}$

$P = 4950 \cdot 1.936 \cdot 10^{-5} \cdot 0.6484$

$P = 0.62$): higher than 0,01

The probability of discharging more than 2 WC's simultaneously

$P(r = 3) = 0{,}0089254$

$P(r = 4) = 0{,}0009580$

$P(r = 3) + P(r = 4) +++ = 0{,}009883$

More than 4 WC's in simultaneous use will change the number in the fifth decimal and higher. Three and more WC's give a probability of simultaneous use of 0,009 ....

Thus the probability will be less than 0,01 for more than 2 out of 100 WC's discharged simultaneously.

According to National Plumbing Code (3) p. 24-20, the peak load period for WC is at the same time as for the kitchen sink. The bathtub has a longer discharging time than a kitchen sink and gives a heavier loading. Designing for simultaneous use of WC and bathtub should therefore give a rather safe calculation of the chance to avoid annoying bubble noises. However, this hypothesis must be proved by testing in practice.

References

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Table 1 Relationships between the activities, the performance related to use and the sanitary fixtures

The importance of the performance
essential = ■
some importance = ▨
particular importance under special circumstances = □

		PERFORMANCE REQUIREMENTS DIRECTLY RELATED TO USE																					Performance requirements related to other needs			
		1. provide water of desired quality	2. supply water in an acceptable way	3. provide adequate flow of water (quantitative)	4. provide water at various places	5. supply water inside the sanitary appliances	6. provide water at the desired time	7. provide adjustable flow of water	8. provide water of a suitable temperature	9. maintain a desired quantity of water	10. have a suitable height	11. have a suitable shape	12. have arrangements for equipment desired near the appliance	13. collect excess water	14. carry off excess water	15. keep objects away from the drain	16. carry off fecals and other waste materials	17. provide suitable cleaning of the body after using W.C.	18. provide support for the body during use	19. washing clothes	20. washing up	21. provide space for activities by the sanitary fixture	22. carry off rain water	23. carry off ground water	24. put out fire	25. ease of replacement, maintenance and alteration
Personal hygiene	Use of WC for disposal of feces and urines		■	■		■	■				■	■	■			■	■	■	■			■				■
	Washing of the body	▨	■	■	■	■	■	■	■	■	■	■	■	■		■		■	■			■				■
	Washing of sick and elderly people and invalids	▨	■	■	■	■	■	■	■	■	■	■	■	■		■		■	■			■				■
Food preparation	Tapping or drawing of drinking water	■	■	■			■	■	■		■		▨	■	■	▨						■				■
	Washing and cleaning for food preparation	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	□					■				■
	Washing dishes and cooking utensil.	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	□				■	■				■
	Disposing of waste water and food waste										■	■		■	■	■						■				■
Cleaning the inside of the house	Washing floors, walls and ceilings	▨	□	■	□		■		■		□	□	■	▨	■	■	□		■			▨				▨
	Cleaning windows, stairs and furniture	▨	□	■			■		■		□	□	■	▨	■	■			□			▨				▨
	Cleaning technical equipment etc.	▨	□	■	□		■	□	■	■	■	■	■	■	■	■						■				▨
Washing clothes and household textiles	Soaking, washing and rinsing clothes	□		■		■	■	■	■	■	■	■	■	■	■	■				■		■				■
	Dampen clothes for ironing		□				■		■																	▨
	Drying clothes													■	■							■				▨
Spare time activities	Cleaning painting implements		■	■		■	■	■	■	■	■	■	■	■	■	■	□					■				■
	Developing films	□	■	■	□	■	■	■	■	■	■	■	■	■	■	■	□					■				■
	Washing the car		■	■	■	□	■	■			▨		■	□	■	□						▨				■
	Watering the garden		■	■	■		■	□			▨		□									▨				■
Factors influenced by nature	Put out fire		■	■	■		■							□	□							▨			■	■
	Carry off rain and ground water										□			■	■	■							■	■		■
Fixtures																										
	faucets	■	■	■	■	■	■	■	■		■	□							□	□	□	■			□	■
	waste water sink	□	■	■		■	■	■	■		■	■	■	■	■	■	□		■		□	■				■
	food waste grinder										■						□									■
	floor drain	□	■	■	■	□	■	■	■		■	□	■	■	■	■			□			■				■
	lavatory	□	■	■	□	■	■	■	■	■	■	■	■	■	■	■			▨			■				■
	kit-hen sink	■	■	■	□	■	■	■	■	■	■	■	■	■	■	■			▨		■	■				■
	water closet		■	■		■	■				■	■	■	■	■	■	■	■	■			■				■
	laundry tub	□	■	■		■	■	■	■	■	■	■	■	■	■	■			■	□		■				■
	clothes washing machine	□	□	■		■	■		□	■	■	■	■	■	■	■			■	■		■				■
	dishwasher	■	□	■		■	■		■		■	■	■	■	■	■			■		■	■				■
	shower-bath	▨	■	■	■	■	■	■	■	□	■	■	■	■	■	■		□	■			■				■
	bath tub	▨	■	■	■	■	■	▨	■	■	■	■	■	■	■	■			■			■				■
	drinking fountain	■	■	■		■	■		□		■	■		■	■	■			■			■				■
	bidet	▨	■	■		■	■	□	■	□	■	■	■	■	■	■		■	■			■				■
	hose bib or sill cock		■	■	■		□		□		■		■		□				□			■			□	■
	car washing facility		■	■	■	□	■	■	■		■	□	■	■	■	■			□			■			□	■
	wash basin for photographic dark room and other hobby activities	□	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■			■				■
	roof or area drain					□					■	■		■	■	■			□				■			■
	subsoil drain										□			■	■									■		■
	fire sprinklers, nozzles and hose connections		■	■	■						■											▨			■	■

Table 2 Connection between influencing factors and performance requirements

INFLUENCING FACTORS			REQUIREMENTS
On the installation as a result of use	On the installation as a result of its environment (climate, constructions etc.)	From the installation to the environment	Performances required by the influencing factors
1. explosion hazard			1. provide safety against explosion
2.		noise caused by tapping and use	2. reduce noises from the use of water
3.		noise from the flow of water	3. reduce noise from water current
4.		noise because unsmoothly working	4. avoid noise because unsmoothly working due to thermal expansion etc.
5.		noise from airbubbles in traps, vibration	5. avoid bubble noises
6.	vibration - water hammer	vibration	6. reduce vibrations and water hammer
7. damage by wrong use, impact, scratches etc.		damage by water	7. provide safety against damage caused by wrong use and wrong equipment
8. soiling-static electric attraction of dust	dust (air/ventilation)		8. facilitate the cleaning of external surfaces and surroundings
9.		blocking-up of pipes with waste materials	9. reduce need for cleaning waste pipes and facilitate internal cleaning
10. effects of heat transfer	temperature changes	heat emission	10. reduce heat transfer and withstand temperature changes
11.	frost		11. withstand the effect of frost
12.	influence of light		12. withstand the effect of light
13. condensation	condensation	dampness	13. withstand the effect of moisture
14. water pressure		water leakage	14. withstand leakage
15. weight- and pressure-loading	weight- and pressure-loading, settlements	weight- and pressure-loading	15. provide safety against weight- and pressure loading
16. wear and tear through age and use	external and internal corrosion, damage during maintenance	damage during maintenance	16. reduce damage from maintenance and corrosion
17.		weakening of the construction through passages for piping	17. reduce need for space and the weakening of the structure by passages for piping
18.		pollution of nature	18. conserve the nature
19. discolouring	discolouring	discolouring	19. keep up the appearance
20.	growth of bacteria and vermin	growth of bacteria and vermin	20. control growth of bacteria and entry of vermin
21.		smell	21. prevent irritating smells from sewer gases
22.	effect of fire	spreading of fire	22. avoid spreading of fire and reduce its hazards

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Sizing of Water Heating Equipment

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This paper contains the results of studies made on 162 buildings throughout the U.S.A. to determine the nature of hot water use in order to establish design criteria for sizing water heating equipment in various types of buildings.

An extensive search of the literature was conducted and analyzed, and there is an extensive bibliography and list of references on this subject available.

Meters were installed in the cold water inlet to water heating systems and hourly readings were taken for periods of up to 1½ years. Data was collected and organized in 10 categories of buildings, men's college dormitories, women's college dormitories, motels, nursing homes, office buildings, food service facilities, apartment houses, elementary schools, junior high schools, and high schools. Test data was analyzed with respect to peak hourly, daily and average flow rates in order to compare with previously available information. Further analysis was done on multiple-hours use of hot water, and curves were drawn representing an infinite number of relationships between storage capacity and recovery capacity, any of which will adequately meet the requirements for hot water in each type of building.

Some of the factors that influence hot water consumption are discussed. The influence that hot water temperature has on demand and consumption is analyzed. New definitions are developed for efficiencies in connection with water heating systems. Limited information on energy consumption of water heating systems is discussed. Safety factors are recommended. There is some discussion on instantaneous flow rates based on data extrapolation.

Typical profiles for each category of building are shown with hour-by-hour flows for the day in which the peak hourly demand occurred, the day in which the peak daily demand occurred and the hour-by-hour average of all test data for the particular building selected.

With this information it is now possible to make an economical selection of water heating equipment, based on both first cost and operating cost. Comparing the recommended sizing methods with those methods previously used shows a significant reduction in both storage capacity and recovery capacity for most types of buildings.

Cette communication contient les résultats d'une enquête faite sur 162 bâtiments répartis dans tous les Etats-Unis, afin d'établir des critères d'étude pour l'équipement d'eau chaude dans divers types de bâtiments.

Une large recherche bibliographique a été faite sur le sujet et l'on dispose à présent d'une importante bibliographie ainsi que d'une liste de références.

Des compteurs furent installés sur les tuyaux d'arrivée d'eau froide des installations d'eau chaude, et des relevés effectués toutes les heures sur des périodes s'étendant jusqu'à 18 mois. Les informations recueillies ont été classées selon 10 catégories de bâtiments: dortoirs de collèges masculins, dortoirs de collèges féminins, motels, bâtiments hospitaliers, bureaux, installations alimentaires, maisons locatives, écoles primaires, lycées, écoles supérieures. On a analysé les résultats en fonction des maxima de consommation horaire et journalière, ainsi que du débit moyen, afin des les comparer avec des informations antérieures disponibles. On a poursuivi l'analyse pour des consommations d'eau chaude sur plusieurs heures, et tracé des courbes traduisant un nombre infini de rapports entre la capacité de stockage et la capacité de récupération, dont n'importe lequel satisfera les demandes d'eau chaude de chaque type de bâtiment.

On examine certains des facteurs qui influencent la consommation d'eau chaude. On analyse l'influence que la température de l'eau chaude a sur la demande et la consommation. En rapport avec les installations d'eau chaude, on développe de nouvelles définitions de rendement. Des informations limitées sur la consommation d'énergie des installations sont examinées. Des facteurs de sécurité sont recommandés. On accorde une certaine attention au débit instantané déduit par extrapolation.

On donne, pour chaque catégorie de bâtiments, des profils typiques de débit, heure par heure, pour le jour où le maximum de consommation horaire s'est produit, le jour de consommation journalière maximale, et la moyenne heure par heure de tous les résultats obtenus pour un bâtiment particulier sélectionné.

Avec ces informations, il est maintenant possible d'opérer une sélection économique des équipements, fondée sur les frais d'installation et les frais de fonctionnement. Une comparaison des méthodes recommandées de calibrage avec les méthodes utilisées auparavant révèle une réduction importante de la capacité de stockage de même que de la capacité de récupération pour la plupart des types de bâtiments.

Key words: Domestic hot water systems; hot water usage; hot water system design; hot water heating; survey of hot water use.

1. Introduction

During the last five decades virtually no significant work has been done to evaluate the performance of service water heating systems in commercial and institutional buildings. The design criterion that has been used is recognized to be quite conservative, resulting in overdesigned systems.

Nowhere in current literature have living habits been mentioned along with their impact on hot water demand and consumption. This is because most of the data in use was based on living habits of people prior to 1920. Since that time, there has been an enormous change in living habits, such as the shorter work week, increased leisure time and more traveling. There is also widespread use of new appliances in apartments and commercial establishments.

Average hot water consumption is needed for estimating operating costs. In some types of buildings, the annual cost for water heating can exceed the cost of space heating, and average consumption data has not been available.

This paper presents new methods for sizing storage water heating equipment, which were derived from hourly metered tests of hot water use conducted in 162 buildings throughout the USA for periods of up to 1½ years.

Oversized equipment results not only in inefficient operation and higher first cost for the user, but also creates unnecessary peak demands for building energy systems.

2. Method of Conducting Tests

Various utility companies throughout the USA were requested to install metering equipment and to collect basic data. Prepared data books provided forms for recording metered information and the physical characteristics of each building as they might pertain to hot water use.

Preliminary analysis of test data showed no discernible difference in hot water consumption due to geographical location. Although fairly good geographical distribution of tests was obtained, it was decided to obtain as many tests as possible while compromising somewhat on location.

3. Metering

For each test, a recording water meter was installed in the cold water supply line to the hot water heating system. To record water temperatures, some tests used recording thermometers, but in each test visual observations of inlet and outlet hot water temperatures were made periodically.

The meters that were used were quite varied, ranging from expensive magnetic flowmeters to cameras mounted over standard water meters with timers set to take one frame per hour. Many companies had meters that were used for other purposes, while others borrowed them from local water companies.

It was determined that high accuracy of the metering equipment was not of prime importance. Since the flows varied widely, accuracy within ±5% was considered adequate. Accuracy at peak flow is usually better and this was more important than the average accuracy. Overall accuracy could not be estimated.

4. Test Data

Hourly test data were requested for a period of from 3 months to 1 year. Although in a few cases it was not possible to obtain data for longer than one week, most tests were for several months, and some tests were conducted for longer than 1 year. All data were given equal weight in the analysis.

Forms were provided for reporting the metered data, as well as information on the building and the various items that used and influenced the use of hot water.

5. Summary of Tests

Table A summarizes the number of tests received. However, not all of them were used, for various reasons.

Most of the tests that were not used included functions in the building and on the hot water system that were not related to the primary function of the building, usually food service facilities whose sizes were unrelated to the occupancy of the primary building.

Table A. Test Summary

Category	No. of tests	No. of tests used
Men's dormitories	10	8
Women's dormitories	10	8
Motels	22	15
Nursing homes	14	13
Office buildings	16	6
Food service establishments	28	25
High-rise apartments	12	11
Garden apartments	16	15
Elementary schools	16	14
Junior high schools	5	4
Senior high schools	13	10
Totals	162	129

6. Data Reduction and Analysis

The general method of approach to data reduction and analysis was determined to be a manual one. The use of data processing equipment was evaluated and discarded due to the non-uniformity and mass of the data.

The test data for each building were reviewed for validity and compared cursorily to other tests in the same category. Unusually high or low results were investigated further.

Data reduction proceeded when all tests in a category were complete. The physical characteristics of the buildings were tabulated along with information on the hot water system. The data were scanned and the 10 highest peak values of gal/hr and gal/day were determined for each building. These first 10 peaks were then divided by various physical quantities associated with each category -- such as the number of people or the number of units.

Curves were then plotted, with gal/hr or gal/day against peak number for each test, and for each physical quantity selected. Visual observation of the curves then determined which physical quantity most influenced the hot water use while providing the best results. Peak daily and hourly flows were then selected for recommendations, sometimes eliminating a few extraordinary peaks.

Once the proper physical quantity in each category was determined, it was an easy matter to compute the average hot water consumption by dividing the total hot water consumption during the test period by the length of the test in days.

To find relationships between storage and recovery capacities, it was again necessary to scan the data for the maximum 2-hr, 3-hr, 4-hr, etc., through 24-hr peak combinations of conditions for multiple hours flow.

The minimum hourly recovery rate was found by dividing the peak daily requirement by 24. Curves showing recovery vs storage were plotted on the same basis as the peak hourly and daily demands.

Finally, one test most typical of a building in each category was selected, and a 24-hr flow profile was plotted to show hourly flows for the day in which the peak hourly demand occurred, the day in which the peak daily demand occurred, and the average use in each hour over the test period. Selection was based on similarity in appearance to most buildings in that category and approach to peak and average flows.

7. Recovery vs Storage Curves

The key to proper selection of storage water heating equipment lies in choosing among an infinite number of combinations of storage and recovery capacity that will meet the peak hourly demand, the peak daily demand and any combination of hourly demands in between.

In addition, it is necessary to provide for a minimum recovery rate, so that the system will be able to handle hot water requirements after a period in which the peak use occurs. The minimum recovery rate is established by dividing the peak daily demand by 24. The resulting number can then be "rounded up" to the next highest convenient figure, thus allowing a small safety factor. Previous methods used divisors of 10 and 20 to determine minimum recovery rate, and therefore had substantial excess capacity built in from the start.

The theory of using storage hot water systems is based on the fact that the water stored in the tank can be used to meet peak hourly demands that are significantly greater than the hourly recovery capacity, thus allowing hourly energy consumption to be minimized and spread throughout the day.

The peak 1-hr use can be satisfied by either an "instantaneous" system designed for that flow rate, or by a system that stores that quantity of water (theoretically without any recovery capacity). By plotting a curve of recovery rate vs storage capacity, it can be shown graphically that any point on a line connecting the peak-hour requirement for both recovery and storage will satisfy the demands of the system.

The peak 2-hr demand must be equal to or less than twice the peak 1-hr demand. This 2-hr peak (taken alone) can be satisfied by having the total quantity of hot water required during these 2 hrs in storage. It can also be satisfied by an "instantaneous" system having one-half of the 2-hr peak as its recovery capacity. Plotting the total quantity of hot water required during this 2-hr peak as recovery capacity, and connecting these two points, it can be seen that any point on this line will satisfy the 2-hr peak demand of the system, except when the 1-hr peak occurs during this time. However, it is seen that the line previously plotted for the 1-hr peak extends higher on the curve, particularly near the higher recovery rates.

Therefore, if we make such a series of curves for the 1-hr, 2-hr, 3-hr, 4-hr, through the peak 24-hr requirement, and connect the highest of all of the peaks that occur on this family of curves, we will be able to satisfy any demand placed on the hot water system. This holds true only for the test for which these numbers are plotted.

If we then draw this same family of curves for each of the buildings tested, and select the highest peaks of all of the curves, we should then have a new curve that will satisfy any series of peaks that would occur in any of the tests.

In addition, we must "bottom out" our curve with the minimum recovery rate, so that the system is prepared to meet the requirements for the following day.

The relative shape and slope of the storage vs recovery curve is indicative of the rate of use of hot water during the day, the relation that the peak-hour demand has to the average hot water demand, and the ratio of the maximum hourly use to the maximum daily use of hot water for each category of building. In buildings where the duration of the peak use of hot water is 1 or 2 hrs, the slope of the curve is steep. Where the hot water use is more uniform throughout the day, the curve becomes "flatter."

8. Recommendations

The information presented here consists of recommendations for sizing central storage type water heaters. General descriptions of the major factors determining the hot water requirements for typical buildings in each category are presented as a guide. Unless the expected hot water use is substantially less than that for a typical building in a category, it is not recommended that the water heater capacity be reduced. When combinations of uses occur in a building that will use a central common water heater, the recovery and storage capacities for each category should be added together.

When unique hot water requirements exist in a particular building, the designer should increase the recovery and/or storage capacity to account for this use.

Dormitories - Fig. 1: Domestic hot water requirements for college dormitories generally include showers, lavatories, slop sinks and washing machines. The peak demand usually results from the use of showers. Load profiles and hourly consumption data indicate that peaks may last 1 or 2 hrs and then taper off substantially. These peaks occur predominately in the evening, mainly around midnight. The figures do not include hot water use for food service.

Motels - Fig. 2: For motels, domestic hot water requirements are for tubs and showers, lavatories and general cleaning purposes. The recommendations are based on tests on low and high-rise motels located in urban, suburban, rural, highway and resort areas. The peak demand, usually created by the use of showers, may last 1 or 2 hrs and then drop off sharply. Food service requirements are not included.

Nursing Homes - Fig. 3: Hot water is required in nursing homes for tubs and showers, wash basins, slop sinks, kitchen equipment with food service for patients and for general cleaning purposes in the building. These figures include hot water for kitchen use. When other equipment, such as for heavy laundry and hydro-therapy purposes, is to be used, their additional hot water requirements should be added to those recommended.

Office Buildings - Fig. 4: Hot water requirements in office buildings are primarily for cleaning and lavatory use by occupants and visitors. Hot water use for food service within office buildings should be considered separately.

Food Service Establishments - Fig. 5: Hot water requirements for food service establishments are primarily for dishwashing. Other uses include food preparation, cleaning pots and pans and floors, and hand washing for employees and customers. The recommendations of hot water requirements are for the serving of food at table, counter, and booth seats, and to parked cars. Food service establishments that use throw-away service exclusively are not included.

Dishwashing, as metered with other hot water requirements in these tests, is based on the normal practice of dishwashing after meals but not on indiscriminate or continuous use of machines irrespective of the flow of soiled dishes. The recommendations include the hot water supplied to dishwasher booster heaters.

Apartments - Fig. 6: The hot water requirements for both garden type and high-rise apartments are for one and two-bath apartments, showers, lavatories, kitchen sinks, dishwashers, clothes washers and general cleaning purposes. Clothes washers can be either in the individual apartments or centrally located. These data apply to central water heating systems only.

Elementary Schools - Fig 7: Hot water requirements in elementary schools are for lavatories, cafeteria and kitchen use and general cleaning purposes. When showers are used, their additional hot water requirements should be added to those recommended. The recommendations include hot water for dishwashing machines, but not for extended school operation, such as evening classes.

High Schools - Fig. 8: Senior high schools, grades 9 or 10 through 12, require hot water for showers, lavatories, dishwashing machines, kitchens, and general cleaning purposes. Junior high schools, grades 7 through 8 or 9, have hot water requirements similar to those of the senior high schools. Where no showers are included, junior high schools would follow the recommendations made for elementary schools.

In both junior and senior high schools, requirements for hot water are based on daytime use. The recommendations do not include hot water usage for additional activities, such as night school. In such cases the maximum hourly demand will remain the same, but the maximum daily and average daily usage will be increased, usually by the number of additional people using showers, and, to a lesser extent, the eating and washing facilities.

9. General

Observed peak hourly and daily demands for various categories of commercial and institutional buildings are shown in Table I. These demands, for central storage type hot water systems only, represent the maximum flows metered in over 160 buildings throughout the United States. Caution must be used in applying these figures to very small buildings.

Also shown in Table I are average hot water consumption figures for these buildings. Averages for schools and food service establishments are based on actual days of operation, while all others are based on total days.

Figs. 1 through 8 show relationships between recovery rate and storage capacity for the various categories of buildings. Any combination of storage and recovery rate capacity that falls on the proper curve will satisfy the requirements of the building. These curves should not be used for sizing instantaneous or semi-instantaneous water heaters.

These curves may be used to select water heaters having either fixed storage or recovery capacities, by varying either recovery or storage requirements. Where hot water demands are not coincident with electric, steam or gas demands, water heater inputs can be selected so as not to create unprecedented energy system demands, and the corresponding storage tank size can be selected from the curves.

The recovery capacities shown represent the actual hot water flow required, and do not take into account system heat losses. Heat losses from storage tanks and recirculating hot water piping should be calculated and added to the recovery capacities shown. With large uninsulated storage tanks, and extensive lengths of uninsulated hot water supply and return piping, it may be necessary to substantially increase the recovery capacity.

The storage capacities shown are considered net requirements. On the widely accepted assumption that 70% of the hot water in a storage tank is usable, the actual storage tank size should be increased by 43% to compensate for the "unusable" hot water.

Figs. 9 through 19 show hourly flow profiles for a typical building in each category. These buildings were selected from actual metered tests, but are not necessarily typical of all buildings in each category. Flow profiles are shown for the day in which the peak hourly demand occurred, for the day in which the peak use of hot water occurred, and for the average of all days during which the metering took place.

10. Summary and Conclusions

The research of the literature showed that there was not only a tremendous lack of valid background information upon which to base the sizing of water heating equipment, but also that the state-of-the-art today is filled with "educated guessing." It is hoped that this work will stimulate others to continue and develop recommendations for other types of buildings.

Among the designers who were surveyed it was seen that there was a vacuum to be filled in this area, and we hope that this work has begun to reduce this vacuum.

Although the geographical distribution of tests favored the eastern half of the country, it is felt that any slight difference in hot water demands due to location will be more than compensated for by the method used in selecting the peaks. We were able to find nothing in the test data to indicate that people in one part of the country used more, or less, hot water than in any other. We did find that people influence hot water consumption to a far greater extent than any other possible variable.

Recirculating hot water systems do not affect the size of the water heating equipment except insofar as they affect recovery rate, which must be increased to account for any heat losses in the system.

Although the use of 140 F hot water supply temperature is quite common, it should not be accepted without applying some judgment to the application. It is hoped that more work will be done to establish better guidelines for selecting hot water temperatures.

Even though few installations are made today without insulation on the storage tank and piping, this heat loss and its effect on system efficiency should be considered. With the information presented here, it is now possible to make an analysis of these factors in hot water systems and come to a reasonable economic conclusion. Increased cost for insulation can, in most cases, be economically justified.

Care is advised in the indiscriminate use of this information. While the recommendations are in an easy to use form, they are not a substitute for the application of the designer's judgment to the particular problem he is faced with at the moment. For buildings not covered by this program we still must recommend the previously used methods, until such time as more work is done in testing these types of buildings. While these recommendations have safety factors of two and three for some of the buildings in a given category, they have been selected to provide adequate hot water for all of the buildings tested in that category.

11. Recommendations for Future Research

Since it is people, not the fixtures themselves, that influence the use of hot water, research should be continued both to verify these recommendations and to make changes as living habits and building uses change.

The categories of buildings for which recommendations are made provide the maximum benefit to the public, commensurate with a reasonable expenditure and effort. Many other types of buildings should be metered and analyzed. Further study should be given to buildings with combination uses.

The influence of tank and line heat losses on recovery capacity has yet to be field verified.

Very little is known about temperature distribution and stratification in hot water storage tanks, particularly under transient conditions of flow. This results in possible oversizing of storage tanks. If there is an excess of 25 gal of hot water stored for each person in the United States, this excess tank capacity alone is over 5 billion gal.

There has been no work done to establish proper hot water supply temperatures for each type of building or types of uses within buildings. In some part of the country legislation has been passed to limit temperatures in certain types of buildings to as low as 110 F.

12. Acknowledgments

We wish to express our appreciation to the Edison Electric Institute, New York, N.Y. and its staff and member companies for making this work possible under the Commercial Building Water Heating Research Project (EEI RP-61) and for donating the results to the public through ASHRAE.

We are grateful to the owners, managers and operating personnel of the 162 test buildings for granting permission for access and installation of metering equipment.

13. References

(1) Spielvogel, L.G., Service Hot Water Sizing Methods, Air Conditioning, Heating and Ventilating (Sept. 1968)

(2) Spielvogel, L.G. and Werden, R.G., Sizing of Service Water Heating Equipment in Commercial and Institutional Buildings, ASHRAE Bulletins and Transactions 1969, ASHRAE Journal (Aug. 1969)

(3) Hot and Cold Service Water, Chapter 35, ASHRAE Guide & Data Book 1970

(4) Spielvogel, L.G., New Concepts for Sizing Storage Water Heaters, Building Systems Design (Nov. 1969)

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Table 1 .... Hot Water Demands and Use for Various Types of Buildings

Type of Building	Maximum Hour	Maximum Day	Average Day
Men's Dormitories	3.8 gal/student	22.0 gal/student	13.1 gal/student
Women's Dormitories	5.0 gal/student	26.5 gal/student	12.3 gal/student
Motels: No. of Units*			
20 or less	6.0 gal/unit	35.0 gal/unit	20.0 gal/unit
60	5.0 gal/unit	25.0 gal/unit	14.0 gal/unit
100 or More	4.0 gal/unit	15.0 gal/unit	10.0 gal/unit
Nursing Homes	4.5 gal/bed	30.0 gal/bed	18.4 gal/bed
Office Buildings	0.4 gal/person	2.0 gal/person	1.0 gal/person
Food Service Establishments:			
Type A—Full Meal Restaurants and Cafeterias	1.5 gal/max meals/hr	11.0 gal/max meals/hr	2.4 gal/avg meals/day*
Type B—Drive-Ins, Grilles, Luncheonettes, Sandwich and Snack Shops	0.7 gal/max meals/hr	6.0 gal/max meals/hr	0.7 gal/avg meals/day*
Apartment Houses: No. of Apartments			
20 or less	12.0 gal/apt.	80.0 gal/apt.	42.0 gal/apt.
50	10.0 gal/apt.	73.0 gal/apt.	40.0 gal/apt.
75	8.5 gal/apt.	66.0 gal/apt.	38.0 gal/apt.
100	7.0 gal/apt.	60.0 gal/apt.	37.0 gal/apt.
130 or more	5.0 gal/apt.	50.0 gal/apt.	35.0 gal/apt.
Elementary Schools	0.6 gal/student	1.5 gal/student	0.6 gal/student*
Junior and Senior High Schools	1.0 gal/student	3.6 gal/student	1.8 gal/student*

* Per day of operation.
* Interpolate for intermediate values.

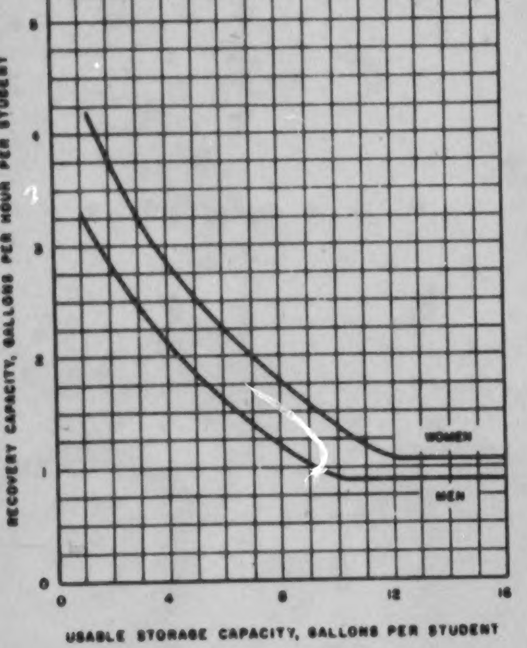


Fig. 1 .... Dormitories

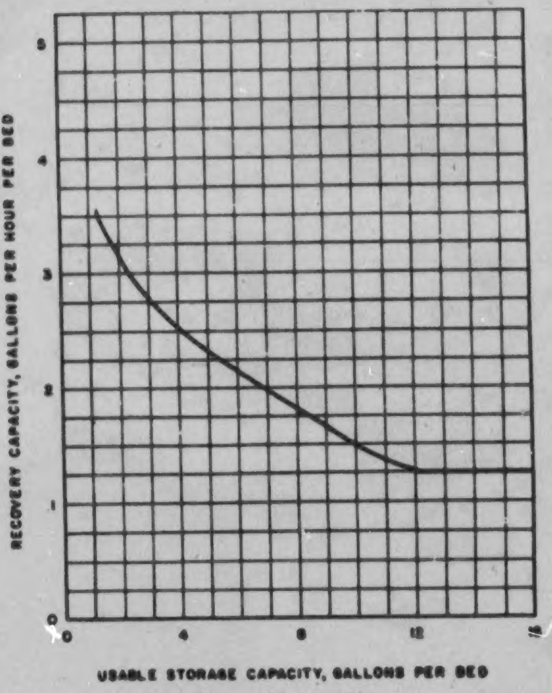


Fig. 2 .... Nursing Homes

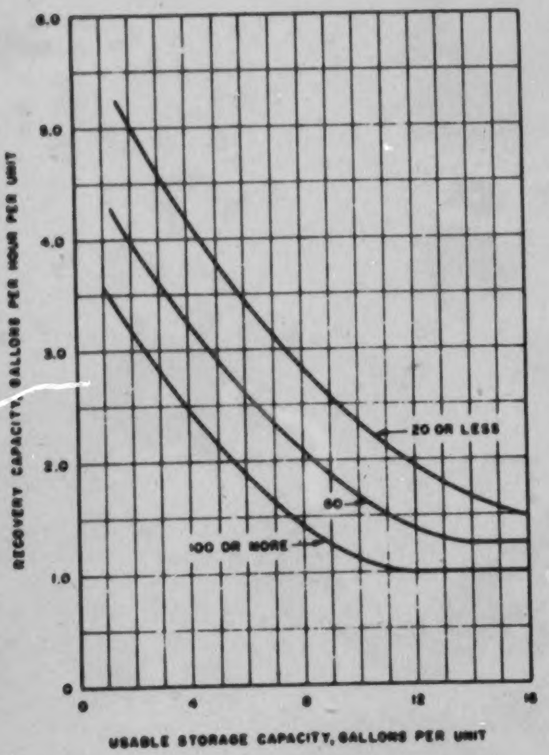


Fig. 3 .... Motels

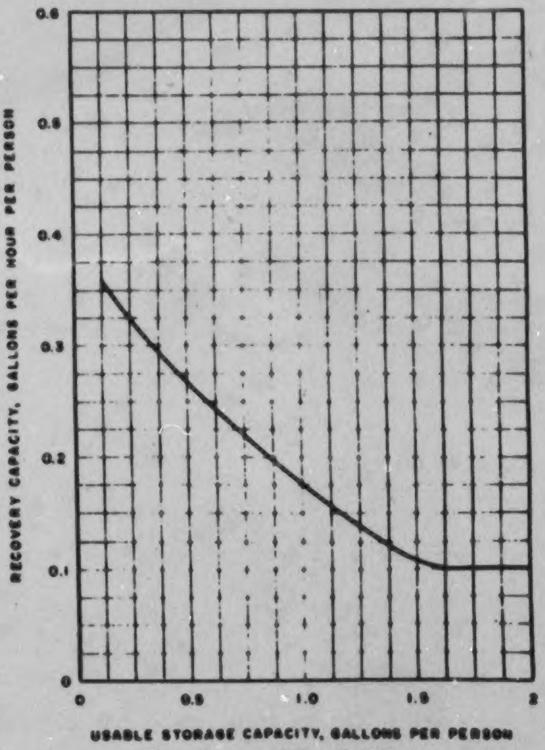


Fig. 4 .... Office Buildings

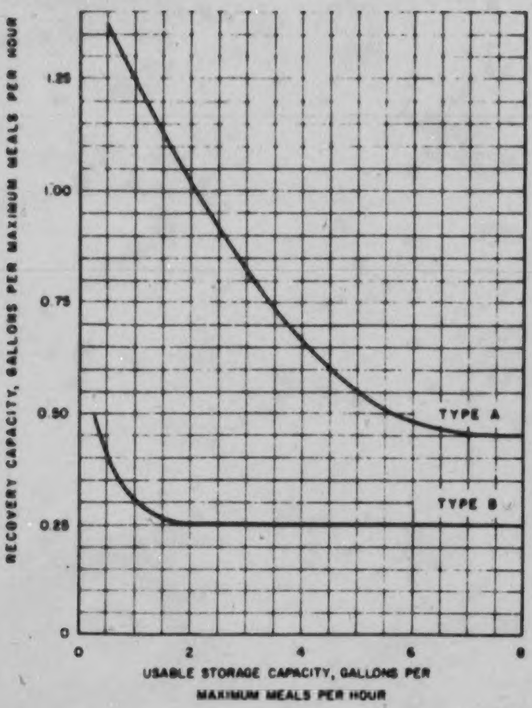


Fig. *5* .... Food Service

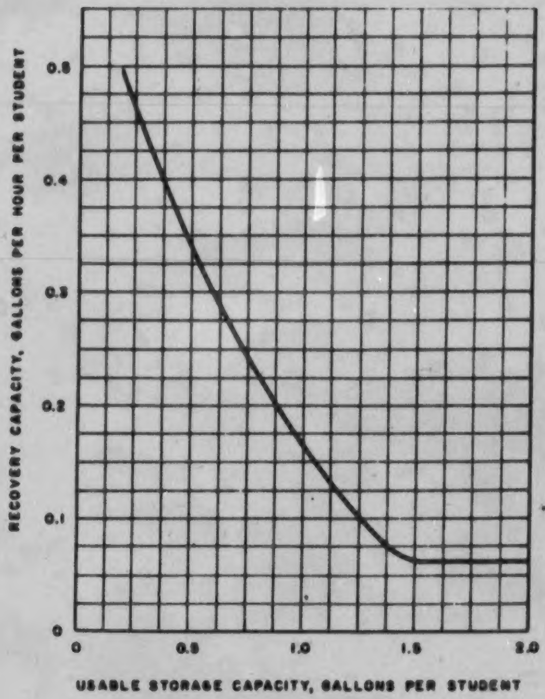


Fig. *6* .... Elementary Schools

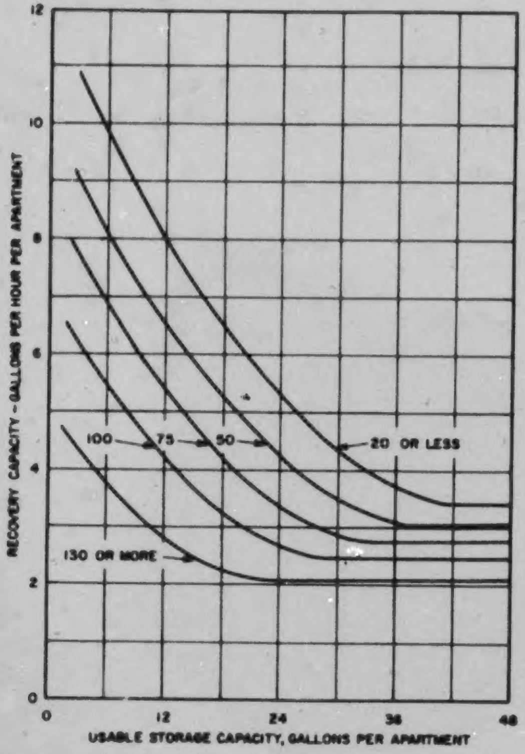


Fig. *7* .... Apartments

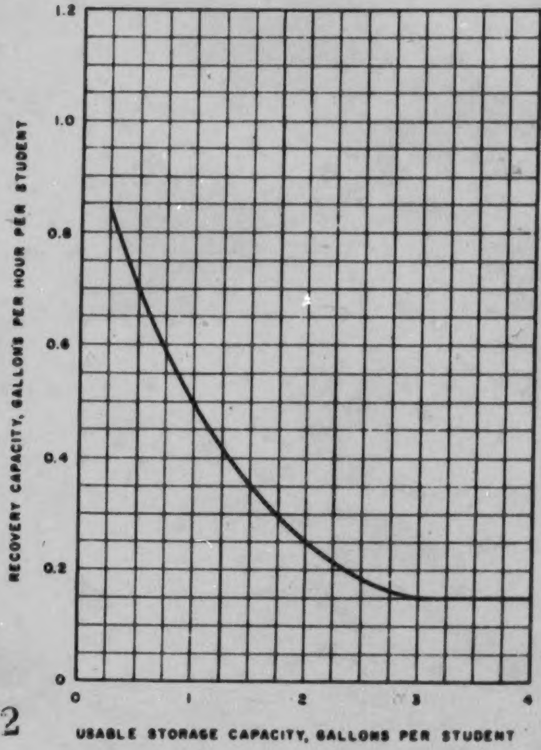
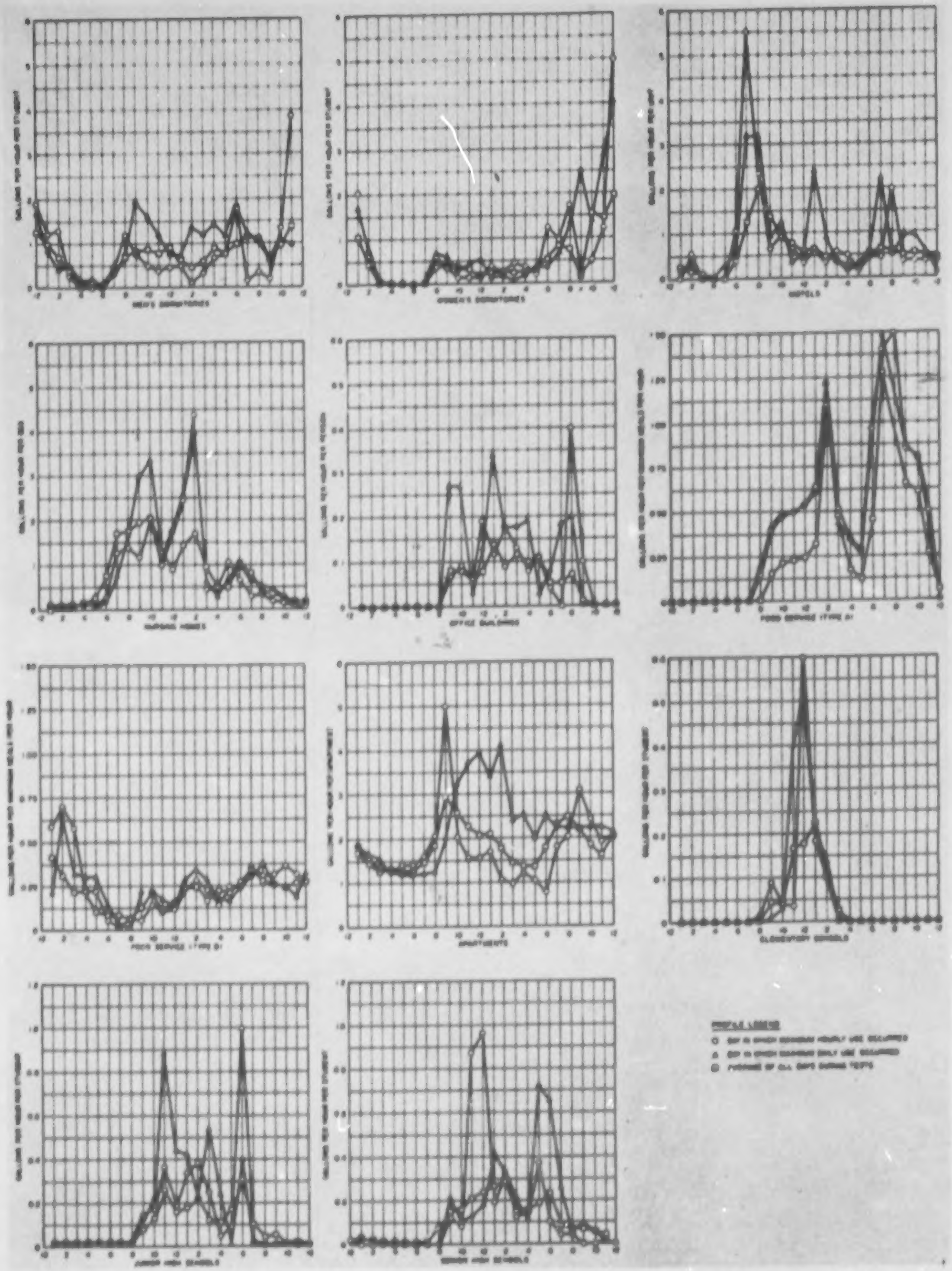


Fig. *8* .... High Schools



Figs. 9 to 19 ... **Hourly Flow Profiles for Various Building Types**

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

The Development of Performance Criteria and Test Procedures for the Piping of Sanitary Drain, Waste and Vent Systems in Residential Service

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The development and use of new plastic materials for drain, waste and vent piping emphasized the need for the identification and definition of service requirements to be used as a basis for minimum performance criteria for these products. Such criteria would have to take account of all of the pertinent application and service factors to which a typical DWV product might be exposed, and to provide for safe and satisfactory performance under these conditions for the projected life of the building. The availability of such criteria would enable the development of materials and the design and engineering of DWV products to more accurately meet the needs of this plumbing service. It would also facilitate the design and evaluation of systems fabricated from various materials.

Several years ago, a task force was established under the auspices of Standards Committee A112 of the American Standards Association (now American National Standards Institute - ANSI) to:

1. Determine the service criteria for residential drain, waste and vent systems;

2. Establish the design criteria and test conditions for plastic DWV materials to meet the service requirements.

The task force, composed of experienced sanitary engineers and others knowledgeable in plumbing engineering identified the following general categories of service criteria: Chemical, Mechanical, Thermal and Environmental. Objective minimum or maximum conditions for each of these criteria in these categories were determined, and test conditions were recommended, based on an assumed fifty year usage.

Following completion of the service criteria, the group determined test procedures, simulating end use conditions and established design criteria consistent with the minimum service criteria for DWV systems. This paper emphasizes the methods used in the study, the service conditions identified as pertinent to DWV exposures, and the criteria established. It then discusses how these criteria were adapted to facilitate adequate performance through appropriate design of plastic DWV piping.

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Le développement et l'usage de nouveaux matériaux plastiques pour tuyaux d'écoulement, de vidange et de ventilation souligne le besoin d'identification et de définition des exigences de service utilisables comme base de critères minimales de performance pour ces produits. De tels critères devraient considérer tous les facteurs, se rapportant à l'application et au service, auxquels un produit E.V.V. typique peut être exposé. Ils devraient aussi assurer une performance sûre et satisfaisante pour la durée anticipée du bâtiment. La disponibilité de tels critères permettrait le développement de matériaux, ainsi que la conception et l'étude de produits E.V.V. qui répondraient mieux aux besoins de la plomberie. Ils faciliteraient aussi l'élaboration et l'évaluation de systèmes fabriqués avec différents matériaux.

Il y a plusieurs années, un groupe de travail avait été formé sous les auspices du Comité des Normes de l'American Standards Association(maintenant American National Standards Institute-ANSI) pour:

1. Déterminer les critères de service pour les systèmes d'écoulement, de vidange et de ventilation dans l'habitation;

2. Etablir les critères d'étude et les conditions d'essai des matériaux E.V.V. plastiques pour remplir les exigences de service.

Le groupe de travail, composé d'ingénieurs sanitaires expérimentés et d'autres versés dans la plomberie, ont défini les catégories générales de critères de service: Chimiques, Mécaniques, Thermiques et d'Environnement. Des conditions objectives minimales ou maximales ont été fixées pour chacun de ces critères et les conditions d'essai ont été recommandées sur la base de 50 ans d'usage.

Aprés l'établissement des critères de service, le groupe a défini les méthodes d'essais, les conditions d'utilisation simulées et réelles et a posé les critères d'étude adéquates aux critères minimales de service requis pour les systèmes E.V.V. Cette communication examine ensuite comment ces critères ont été adaptés pour obtenir plus facilement une performance adéquate grâce à une conception approprié des tuyaux E.V.V. en matière plastique.

Key words: Criteria for DWV pipe; drain, waste, and vent systems; environmental factors; evaluative methods for DWV pipe; thermoplastic pipe.

Introduction

For years, the standards for materials used in sanitary drainage plumbing systems have been governed more by materials available than requirements of the service. Criteria were limited to and defined by the specific properties of the products being used for DWV (drain-waste-vent) systems. While performance of existing products was certainly suitable, as judged by years of experience, no criteria were available to determine the optimum design and performance of DWV piping made of any materials. As new piping materials were developed, offering greater flexibility in design and properties, the need for objective performance criteria became evident.

The Federal Construction Council, responsible for coordinating building technology among Federal agencies, recognized this need and in 1964 requested the National Academy of Sciences to determine the criteria for insuring suitability of rigid thermoplastic DWV piping. This study and its recommendation were reported in the F.C.C. Technical Report No. 52, Rigid

Thermoplastic Pipe and Fittings for Residential Drain, Waste and Vent Systems. [7][1]

While this report was helpful to the various Government Agencies in evaluating the suitability of thermoplastic DWV piping in relation to their programs, it was not widely used by the writers of plumbing codes and standards in developing performance criteria for sanitary DWV piping for housing systems in general. In 1965, a task force was selected under the auspices of Standards Committee A112 of the American Standards Association (now American National Standards Institute - ANSI), to:

1. Identify and select performance criteria for DWV piping [1];
2. Select or develop appropriate test methods and procedures for evaluation of DWV piping [1];
3. By utilizing the information obtained in (1) and (2), present the criteria in a form useful to both the designers and the evaluators of thermoplastic DWV piping [2].

The task force was selected to provide both experience and constructive interest in the program. It included representation from the Federal Housing Administration, Building Research Advisory Board of the National Academy of Sciences, the National Bureau of Standards, American Society of Sanitary Engineering, American Standards Association, a product manufacturer and a material manufacturer.

The following principles were applied by the task force in selecting criteria for DWV piping:

1. The criteria for DWV piping should be those characteristic of the service or exposure conditions of DWV usage and not those which are related to the product or to its design or method of assembly. In short, the criteria should be related to the conditions controlled by the service environment, not to the limitations of particular properties of a given product.
2. Criteria selected need not account for 100% of the potential applications, but must account for those applications that are representative of typical service in housing in the vast majority of installations. For particular situations, the criteria may describe a higher level of performance than would generally be described.
3. Criteria should cover all types of residential use, but distinctions should be made where necessary to account for differences, e.g., between single-family units and multiple-family and high-rise units.
4. Different criteria should be recognized for below and above ground use.
5. Criteria should be confined to use conditions, not handling, transit, etc.
6. Consideration should be given both to initial performance capability and to maintenance of properties over a period of time.

The principal environments to which DWV piping is subjected in housing applications, together with the more significant representative exposures in each environment, were classified as follows:

1. Chemical Environment
    1.1. Internal Exposure: plumbing cleaning agents, sewage and clear-water wastes, drainage, and household chemical wastes.
    1.2. External Exposure: soil and moisture conditions

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[1] Figures in brackets indicate the literature references at end of this paper.

2. Thermal Environment
    2.1. Hot water exposure
    2.2. Thermal shock exposure

3. Mechanical Environment
    3.1. Impact exposure
    3.2. Earth burial load exposure
    3.3. Internal pressure exposure
    3.4. Beam load exposure

4. Biological Environment

5. Weather Environment

6. Fire Environment

Based on a recognition of the various service environments, the procedure followed by the committee in establishing the criteria was:

1. To identify and define the various environmental conditions and variables associated with each type of service exposure.

2. To establish objectively realistic levels of performance for these criteria, either by acceleration of the exposure or by comparison with the performance of known suitable products.

3. To select or develop test procedures, preferably using ANSI or ASTM tests, which both simulate the service exposure conditions and provide for objective and reproducible test results.

Environmental conditions, testing conditions and methods, and criteria were considered independent of materials used and were dependent only on the service conditions encountered.

After identifying and defining a set of service criteria, the task force next applied them to the establishment of a set of design criteria based on a knowledge of the minimum performance requirements dictated by the service environment.

An extensive effort was undertaken to define criteria and to establish quantitative values representing minimum and/or extremes of normal service conditions. Literature research was conducted for knowledge of previous studies on DWV service criteria. Plumbing product manufacturers and engineers were also contacted for information to help in determining service conditions. In the case of impact resistance, where it was not possible to develop performance criteria independently of material properties, the resistance of conventional piping that is satisfactory with respect to this property was used as the minimum level of performance for impact.

The results of this study are applicable to DWV piping for residential buildings of all types, and their applicability covers piping within the buildings as well as piping which connects the house to the public sewer or other point of disposal.

I would like to summarize now some of the work of the task force as it endeavored to relate the environmental conditions, the criteria, and the significance of this work in the engineering design of DWV systems.

1. Chemical Environment

The chemical environment of sanitary DWV systems can be divided into two broad areas: internal exposure to solutions which might be introduced into the drainage system by occupants of the structure, and external exposure to soils surrounding buried piping.

1.1. Internal Exposure

The chemical constituents contained in wastes transported by DWV piping probably impose the single most demanding environmental influence, regardless of the piping material used. All currently used and proposed materials for sanitary DWV piping are susceptible to degradation in some degree by many of the chemicals which might be introduced into a drainage system. One of the key needs is a means of distinguishing between those materials that will and those that will not provide adequate service life in contact with such chemicals.

Chemicals whose introduction into a sanitary DWV system can normally be anticipated include those associated with bleaches, detergents and soaps, household cleaners, and similar products, and also those products used in connection with cooking or with hobbies. Such chemicals would include: inorganic acids, organic acids, alkaline materials, and other oxidizing and reducing agents.

It is necessary to establish such factors as concentrations, temperatures, and exposure time to reflect properly the service environment against which suitability of a piping material should be judged.

On the basis of normal use, the following groups of chemicals with associated concentrations, temperatures, and exposure cycles are considered to represent adequately the in-service chemical environment of DWV systems:

Group 1 Materials
(Most commonly encountered; at room temperature and at 140°F)

Solution	% by Weight in Water
Alkyl-aryl sulfonate (e.g., Oronite, Ultrawet or Nacconol) . .	5%
Hydrochloric acid.	5%
Hydrogen peroxide.	5%
Sulfuric acid.	3%
Sodium carbonate	10%
Sodium chloride.	10%
Sodium hydroxide	10%
Sodium hypochlorite.	5%
Sodium perborate	5%
Sodium acid sulfate.	2%

Piping of a sanitary DWV system can be expected to experience frequent exposure, daily in many cases, to each of these chemicals both at room temperature (73°F) and at 140°F, throughout the intended service life of the system. Such exposure could be for intermittent periods of time not in excess of three minutes, occurring between similar periods of exposure to fresh tap water, and followed by periods of time (six to twelve hours) during which the piping experiences exposure only to ambient- or room-temperature conditions.

The reproducible exposure cycle recommended for use in evaluating suitability to Group 1 solutions, or materials proposed for piping of DWV systems is:

> Exposure to each solution at 140°F for a period of twenty minutes followed by a thorough rinse with cold tap water for a period of five minutes, each hour for seven consecutive hours of five consecutive days, without evidence of corrosion, cracking, swelling or flaking of the exposed surface when tested before and after immersion in accordance with ASTM D543 to measure weight change and ASTM D790 to measure changes in flexural strength and modulus of elasticity.

Group 2 Materials
(Less commonly encountered than Group 1; at room temperature only)

Solution	% by Weight in Water
Ammonium Hydroxide (Technical grade, 20%)	10%
Raw urine	50%
Vinegar (household)	100%

Exposure of piping to these solutions should be similar to that for Group 1 solutions except that occurrence would be at room temperature. The reproducible exposure cycle recommended for use in evaluating suitability to Group 2 solutions of materials proposed for piping of sanitary DWV systems is:

> The cycle and tests used for Group 1 solutions, but with solutions of this group maintained at room temperature (73°F).

Group 3 Materials
(Items of special occurence)

Solution	Grade
Amyl acetate	Commercial
Carbon tetrachloride	Technical
Cottonseed oil	Commercial
Gasoline	High-octane
Hydroquinone	Photographic
Potassium thiocyanate	Commercial
Sodium thiosulfate	Photographic
Stearic acid	Commercial
Toluene	Commercial
Turpentine	Technical
Isopropyl alcohol	USP

Piping of a sanitary DWV system can be expected to experience exposure to each of these chemicals at room temperature only infrequently during the intended service life of the system. The reproducible exposure cycle recommended for use in evaluating suitability to Group 3 solutions of materials proposed for piping of DWV systems is:

> Exposure to each solution at room temperature (73°F) for a period of one minute each day for two consecutive days, with a time-gap of 24 hours between exposures, and with each exposure followed by a thorough rinse with cold tap water for a period of five minutes, without evidence of corrosion, cracking, swelling or flaking of the exposed surface when tested in accordance with ASTM D543 and D790.

1.2. External Exposure

The chemical constituents of the subterranean environment, including moisture, which normally contribute to corrosion of pipelines—the obvious factor of concern here—vary so greatly from one installation site to another that establishing a single representative environmental exposure is precluded. Nevertheless, an exposure providing a sufficient indication of material susceptibility to and rate of corrosion due to the soil of anticipated burial should be required as a basis for owner/user decision making. The following exposure is recommended for use in evaluating suitability, with regard to soil corrosion, of materials proposed for piping of DWV systems:

> Exposure, in accordance with test methods and procedures developed specifically for assessing susceptibility of particular classes of material, to soil/moisture conditions representative of those at the proposed installation site. Conditions, such as cinder fill or salty soil, are very corrosive and DWV piping should be tested by an ASTM procedure to determine suitability.

2. Thermal Environment

The thermal environment of sanitary DWV systems can, like the chemical environment, can be divided into two broad areas: the normal maximum hot- and cold-water exposure cycle, and possible thermal shock which may occur with a sudden change from one to the other temperature extreme.

2.1. Hot Water Exposure

Through review of the technical literature, and discussions with appliance and water-heating equipment manufacturers and engineers, maximum temperature of water entering drainage systems was established as 180°F. The rate of flow possible at this temperature is limited by the discharge rate of the supply pipe and faucet, the amount of high-temperature hot water stored, and the recovery rate of the water heater. Only small-diameter pipe (two inches or less) used to provide immediate drainage from individual fixture units into which such hot water might be introduced would experience exposure to water at this temperature. For larger sized pipe (greater than two inches), used to receive the combined waste water flowing from a number of fixtures, 160°F is more representative of maximum water temperature to be experienced, since mixing of the 180°F water with other wastes undoubtedly will considerably lower the temperature.

Exposure to water of maximum temperature may be continuous for periods of time on the order of two minutes, occurring intermittently between continuous exposures of various durations to water with temperature ranging anywhere from about 65°F to a normal high of approximately 140°F, and periods of time during which the piping experiences exposure only to ambient- or room-temperature conditions.

The reproducible cycle recommended for use in evaluating suitability, with regard to hot-water resistance, of piping proposed for use in sanitary DWV systems is as follows: [3]

> To be deemed suitable for use in DWV systems, pipe of all diameters, when hung horizontally at a slope of 0.25 inches per foot and supported at the maximum span recommended by the manufacturer, should be capable of sustaining the following exposure cycle 750 times without indication—when deflection of mid-span after 750 cycles is extrapolated for 73,000 cycles[2]—of mid-span deflection in excess of one quarter of the difference in elevation between the two adjoining supports:
>
> 1. Hot water flowing continuously, at the temperature and flow rate specified below for specific pipe diameters, for a period of two minutes, followed by a four-minute dwell time, during which there is no flow.
> 2. Cold water flowing continuously, at the temperature and flow rate specified below for pipe of the same diameter, for a period of two minutes, followed by a four-minute dwell time during which there is no flow.

Pipe Diameter (in.)	Hot Water Flow Rate (GPM)	Hot Water Temperature (F)	Cold Water Flow Rate (GPM)	Cold Water Temperature (F)
1½	7½	180	7½	65–75
2	7½	180	7½	65–75
3	15	160	15	65–75
4	15	160	15	65–75
5	15	160	15	65–75
6	15	160	15	65–75

2.2. Thermal Shock Exposure

Through study of DWV system installation procedures, it was ascertained that piping could possibly be exposed to low ambient outdoor temperatures and then to waste water at the maximum defined temperature of 180°F. Assuming an ambient outdoor temperature of -25°F as representative of the low ambient temperature which might be encountered on occasion in some geographical locales, this could result in piping experiencing a thermal shock of 205°F. It is therefore recommended that the following exposure be used to evaluate the thermal shock resistance of piping proposed for use in DWV systems: [7]

> Exposure to 180°F water flowing continuously for a period of one minute at the rates used for testing hot and cold water exposure (section 2.1.) when the piping is at an initial temperature of -25°F.

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[2] 73,000 cycles is considered equivalent of that which would be experienced by piping over a fifty-year life assuming exposure to four of the cycles daily.

To be deemed suitable for use in DWV systems, piping of any diameter, after continuous exposure for 24 hours to an ambient air temperature of -25°F, should, while remaining exposed to this ambient condition, be capable of withstanding 180°F tap water flowing—at the aforementioned rates for pipe of specific diameters—continuously for a period of five minutes without experiencing visible cracking; further, when capped at one end after this exposure, then filled with cold tap water (73°F) and placed under an internal pressure equivalent to that of a ten-foot head of water for fifteen minutes, the piping should show no evidence of leakage.

3. Mechanical Environment

Of the many factors that could be considered to constitute the total mechanical loading environment of piping of DWV systems, those considered potentially significant include: impact forces occurring both during and after installation; loads applied to piping installed below grade as a result of backfill soil and any load superimposed at ground surface in the vicinity of buried piping; internal pressures exerted on piping and joints as a result of blockage of the system after installation; and loads of various magnitude hung from piping run horizontally and exposed along basement ceilings.

3.1. Impact Exposure

No meaningful upper limit can be established for impact loading because sufficient energy can be—and has been—associated with such loads to effect rupture regardless of the material from which piping is made. A need exists, however, that some minimum resistance to impact loading be possessed by piping to be used in DWV systems to offset any accidental and/or abusive treatment. Impact strength is dependent on so many different and such widely varying parameters that selection of a particular value as representative of the actual becomes completely empirical. Nonetheless, an impact strength at 32°F which will offset a five pound weight falling through a distance of five feet (i.e., an impact strength of twenty-five foot pounds) appears to be a reasonable minimum requirement, in as much as this value is representative of the impact strength of piping materials which have proved capable of providing a satisfactory degree of performance in DWV systems. The following exposure is therefore recommended for use in evaluating impact strength of piping proposed for use in DWV systems:

> Exposure at 32°F to the impact provided by a five pound weight falling through a distance of five feet and applied through a striking head having a radius of 0.5 inches, without experiencing visible cracking or permanent indentation in excess of 5% of the original diameter. Pipe specimens should be tested in accordance with procedures detailed in ASTM D2444 [2].

3.2. Earth Burial Load Exposure

The second factor in the mechanical loading environment, i.e., earth burial loads, plus loads superimposed at ground surface in the vicinity of the buried pipe, presents a somewhat more complex problem in that the actual load to be experienced is—at least in part—a function of the reaction of the pipe material to the loads. Rigid pipe—defined here as having a cross-sectional shape which cannot be distorted sufficiently to change vertical or horizontal dimension by more than 0.1% without material damage—supports earth loads, for example, chiefly through high inherent wall or ring strength, and thus, when failure occurs, it is normally by rupture or cracking with little or no deformation when ring strength is exceeded. By contrast, flexible pipe—defined here as having a cross-sectional shape which can be distorted sufficiently to change vertical or horizontal dimensions more than 5.0% without material damage—supports some earth load originally with inherent wall strength, but the full value in supporting earth loads is derived from the capacity to deform without fracture. As the pipe deflects under load, the horizontal axis dimension increases, moving the pipe wall out against the side fills. With development of passive lateral soil resistance pressures in the side quadrants of the enveloping soil, the side fills become increasingly compacted and offer more and more resistance to further deflection.

Flexible pipe normally fails by excessive deflection. Under load, once the top of the pipe passes a point of being approximately flat due to downward deflection and becomes concave upward, complete collapse is possible, as the concave shape will tend to pull the sides of the pipe inward, thereby eliminating the passive side resistance of the soil. Collapse of flexible pipe generally is not imminent until deflection exceeds about 20% of the nominal diameter.

Despite the fact that actual load to be experienced by buried piping is a function of the reaction of the pipe to loading, anticipated superimposed surface loads as well as earth density can be established, and actual loads to be experienced by piping with different characteristics can then be computed in accordance with recognized empirical formulas developed for this use [4,5]. Thus, considering maximum probable superimposed surface load and earth density, it is recommended that suitability of pipe proposed for use in DWV systems be evaluated, with regard to the earth burial environment, in light of the load to be experienced as a result of:

> The static earth load due to burial of the pipe, in earth having a density of 120 pounds per cubic foot at depths from two to eight feet, in addition to an 8,000-pound wheel load applied at the ground surface.

To be deemed suitable for use in the buried portion of a drainage system, the DWV pipe should possess sufficient resistance to crushing to sustain without cracking or rupture, the static loads indicated below for the respective diameters, and sufficient resistance to deflection under the same loads to ensure that diametral deflection does not exceed 5%. The same pipe also should be capable of sustaining the respective equivalent static and dynamic loads given without experiencing diametral deflection in excess of 15% (or cracking or rupture); further, after the equivalent static and dynamic load is removed, residual deflection within thirty minutes should not exceed 5%. Loads for pipe having an outside diameter other than shown in this table may be determined by interpolation.

Pipe Size (in.)	Outside Diameter (in.)	Static Load (lb/linear ft.)	Equivalent Static and Dynamic Load lb/linear ft.
3	3.500	290	585
4	4.500	375	750
5	5.563	460	925
6	6.625	550	1100

3.3. Internal Pressure Exposure

For the internal pressure testing of a system for leakage prior to its operation, a drainage system is normally tested with water, either in its entirety or in sections. If testing is applied to the entire system, all openings except the highest are tightly closed and the system is filled with water to the point of over-flowing. If testing is done in sections, each opening except the highest in the section under test is tightly plugged, and the section is tested with not less than a ten-foot head of water. Leakage testing does establish a concern that adequate joint strength be provided by the method of joining used. The following exposure is recommended for use in evaluating joint strengths of piping proposed for use in DWV systems: [2]

> Exposure to an internal water pressure of 25 psi for a continuous period of fifteen minutes with the water at a temperature of 73°F.

3.4. Beam Load Exposure

In addition to those loads already discussed, there remains the possibility of applications of loads on horizontal pipelines exposed along ceilings. Since the variables of weight, rate of loading, point of application of load in relation to location of hangers or supports, duration of load application, and the like, are numerous, it is necessary to make judgment as to the most probable critical but realistic condition that might be encountered. It appears reasonable that 100 pounds be considered the maximum load in establishing strength requirements for piping to be used in DWV systems and that such a load would be most critical when hung from the mid-span between hangers. The following exposure is therefore recommended for use in evaluating the beam strength of pipe proposed for use in DWV systems: [7]

To be deemed suitable for use in DWV systems, piping of any and all diameters, when

> supported horizontally at the maximum support spacing recommended by the manufacturer, should be capable of sustaining for three hours a 100 pound load without experiencing fracture or cracking or mid-span deflection in excess of 0.25 inches when such deflection is determined at a time between ten and fifteen minutes after removal of the load. The load should be applied at the mid-span between recommended support spacings, at a rate of twenty pounds per second—through a hanger having a two-inch bearing width.

4. Biological Environment

Since the DWV systems handle waste, there is necessarily concern regarding the possibility of damage to pipe and fittings by attack from vermin, bacteria, and/or fungi. Understandably, it is impossible to define the factors which might be considered to constitute the biological environment of a typical DWV system, but susceptibility of piping to attack is dependent nonetheless on whether or not the constituent materials of pipe and fittings are attractive to biological organisms as a source of food; in addition, in the case of fungi and bacteria, susceptibility to attack is dependent on whether ambient conditions of humidity and temperature are such as to encourage their growth; or, for some vermin, on whether pipe and fittings serve as a barrier to discoverable food, such as rats gnawing through pipe to reach water or nutrients inside. General cleanliness of the surroundings, a factor normally controllable to a substantial degree by design or by the residents, can be of considerable importance, particularly with regard to the presence of and consequent degree of potential attack by vermin.

Sufficient evidence [6] exists regarding improbability of damage as a result of attack by rodents, insects and bacteria on piping currently used for DWV systems to make establishment of such criteria unnecessary. A different situation exists, however, with regard to fungi, for which numerous materials, particularly among the organics, offer a potential source of nutriment. The exposure which follows is therefore recommended for use in evaluating suitability with regard to fungus resistance of materials proposed for piping of DWV systems.

> Exposure through inoculation with Aspergillus niger (ATCC No. 6275), and incubation for a period of fourteen days at a temperature of 82°F to 86°F and 85% to 95% relative humidity, without exhibiting visible evidence of fungus growth. [2,7]

5. Weather Environment

It is virtually impossible to establish a meaningful definition of the environment which considers all of the factors normally treated together as constituting the cause of "weathering". The level of energy associated with solar ultraviolet radiation that might interact with the constituent of piping materials in the vicinity of the earth's surface, the level of relative humidity and temperature, the amount and type of precipitation, and other factors, all vary greatly from year to year, from one season to another, and from locality to locality. For the circumstances in which a DWV system or a portion thereof will be subjected to outdoor exposure, some assurance of sufficient resistance to the elements is required. For these systems or portions of systems, it is recommended that the following exposure be used in evaluating weathering resistance of piping material proposed for use:

> Exposure to ultraviolet radiant energy, heat, and humidity and other conditions that are likely to affect the materials being investigated, in accordance with test methods developed specifically for particular classes of material. For plastic piping, ASTM D2501, procedure C is recommended with the requirements that the specimens shall not develop surface irregularities, splits or craze perceptible to the naked eye. The changes in flexural strength and modulus of elasticity of the exposed specimens when compared with that of unexposed specimens shall not exceed ten percent.

6. Fire Environment

Fire safety criteria for DWV systems cannot be disassociated from those of other elements or components of the structure within which such a system is contained. Fire safety for overall construction involves various factors of combustibility—e.g., ignition point of materials, flame spread rate, and the spread of fire and smoke from one room to another; temperature rise on walls and in air spaces in rooms adjacent to rooms in which fire is occurring; considerations of all materials used and their interrelations, and the use of structural devices or special protections, e.g., fire walls, compartmentation, and fire-retardant coatings. In light of the complex nature of the factors determining fire safety and the inextricable interrelationship of DWV systems with other building components, it is important that the DWV system in no way compromise the fire rating of the structure. It is recommended, therefore, that:

> The installed DWV system conform to the fire safety requirements applicable to the type of construction and use of the structure, and that no element of the DWV system be such as to increase the susceptibility to combustion, flame spread or fire hazard of the structure or of any element or portion thereof.

The test methods used should be those standardized ASTM fire tests acceptable to building code authorities for determining and qualifying similar or related building components, the installation of which is continuous throughout the building, for the type of construction in which it is to be installed.

7. Summary

These studies are not meant to be used as product standards nor to disqualify existing products, but to serve as a basis for designing and testing new DWV products and for the improvement of product standards and qualification of new products.

Among the advantages provided by the criteria developed here are:

1. The design and engineering of DWV piping systems to provide a more optimum balance of performance and economic values while insuring that minimum requirements are met for the type of environment and service intended.

2. Greater advantage can be taken of the properties of materials in designing DWV systems.

3. Code and engineering groups will have an objective, soundly engineered reference with which to evaluate and accept DWV products.

4. It will obviate the need for intense, emotional, and often subjective and irrelevant industry conflicts regarding suitability of materials and products; and hopefully, encourage concentration on constructively engineering better and more economical DWV systems.

The committee conducted its work with the highest degree of professional integrity and engineering analysis in arriving at realistic and objective criteria. It is hoped that the results will provide the basis for a constructive technological evolution in the development and use of DWV materials and products, through its contribution to performance-oriented criteria for the design and evaluation of DWV piping.

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Simplified Acoustical Measurement Procedures for Building Code Enforcement

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New and revised building codes now contain specific requirements for acoustical privacy in multifamily dwellings. These performance specifications for sound transmission loss, impact sound insulation, maximum permissible sound power radiated by mechanical equipment and isolation of structural vibration sources must be subject to field measurements to assure compliance with the building code provisions. In most cases the results of these field measurements need only indicate a "pass" or "fail" result.

This paper reviews some of the simplified field test procedures now in use and in process of development.

De nouveaux réglements de construction formulent des exigences spécifiques pour l'isolement acoustique des habitations à appartements multiples. Ces spécifications de performance pour l'affaiblissement du son transmis, l'isolation des bruits de chocs, la puissance acoustique maximale admissible d'un équipment mécanique et l'isolation des sources de vibrations structuales doivent être l'objet de mesures sur place en conformité avec les dispositions du réglement de construction. Dans la plupart des cas, it suffit que les résultats de ces mesures sur place soient traduits par "positif" ou "negatif".

Cette communication passe en revue quelques-unes des méthodes simplifiées de mesure sur place maintenant en usage et en cours de développement.

Key words: Acoustical field measurements; building code enforcement; noise control in dwellings; noise control enforcement.

Most of the new noise control provisions of building codes attempt to regulate the amount of noise that intrudes into the living space from adjacent spaces inside and outside the building. If the noise control requirements are properly written, the effectiveness of the written code depends upon its enforcement.

Noise intrusion into the dwelling can follow two basic paths -- STRUCTURE BORNE-sound transmitted by the vibration of the solid structure of the building; and AIRBORNE-sound transmitted through the air. Determination of code compliance for the isolation of structure borne noise sources can usually be made by non-acoustical measurement procedures. Measurement of the deflection of the isolation device or visual inspection are common procedures. Whether the requirements for the maximum permissible noise output of mechanical equipment or airborne transmission loss have been met must be determined by acoustical measurements.

For example, when measuring the acoustical separation between two conventional rooms for the purpose of code enforcement, the procedure used in obtaining the data need not determine how much transmission occurred through the various potential sound paths, such as: through the partition; through the cracks between the partition and floor and adjacent walls; through connecting ductwork; and through back-to-back outlets, etc. (1)[1]

The building inspector, in his determination of whether the noise control provisions of the code have been met, is not required to concern himself with evaluating the various flanking paths. His concern should be limited to whether the acoustical separation between the apartments has been achieved in accordance with the requirements of the code. In other words, his interest is: Does the acoustical separation "Pass" or "Fail". In order to convert the measured acoustical separation to the specified Sound Transmission Class requirements of the code, a mathematical procedure is followed which need not be done in the field. All that needs to be done in the field is to obtain sound pressure level measurements in both the source and receiving room with a sound source located in the source room. To convert to field measured sound transmission loss, it will be necessary to measure the area of the sound barriers separating the two rooms and in some cases the amount of sound absorption in the receiving room (2) (3). However, these are relatively simple procedures and need not concern us at this time.

A question may arise regarding responsibility in the event the test indicates failure because of flanking transmission. If the flanking transmission is through a ventilating duct, will the building inspector's notice of violation so state? The answer I submit is, "NO!". The reason for the failure to meet the requirements should be determined by another investigator, possibly acousticians employed by the manufacturer, architect or owner of the building. After the responsibility has been fixed and the flanking path corrected, the Building Inspector can again conduct the "Pass" or "Fail" measurement and if a passing grade is obtained, remove the violation.

Following this reasoning, only one measurement of sound pressure levels (in octave bands) is required for the Building Inspector to determine whether the noise levels in living spaces are adversely affected by mechanical equipment located inside or at the exterior of the building. Also, with the aid of a tapping noise source, he can determine whether the impact transmission loss of a floor-ceiling construction meets the requirements of the code (4) (5)

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[1] Figures in brackets indicate the literature references at end of this peper.

The various standards that outline the methods of conducting these tests require, as stated above, the measurement of sound pressure levels in dB over a frequency range of 100 to 4000 Hz. A single overall measurement is not sufficient. Substantial information is required as to the frequency distribution versus sound pressure level. Noise Criterion Levels require 8 to 10 octave band measurements. Sound transmission class calculation requires 16 measurements at 1/3 octave bands in the source room, 16 in the receiving room and in order to make sure that the signal radiated by the test sound source is sufficiently high not to be affected by background noise from traffic or other sources, it is usually necessary to obtain 16 more 1/3 octave band measurements in the receiving room when the sound source is shut off. Measurement of the impact transmission loss of the floor-ceiling construction also requires 16-1/3 octave band measurements in the room below, with the tapping machine operating on the floor above. Again, the same measurements must be made without the tapping machine to assure that the background noise level did not contaminate the data.

For determination of "Pass" or "Fail" of the airborne and impact transmission requirements for one room, I have just enumerated at least 88 measurements of sound pressure level in octave bands or 1/3 octave bands. Multiply this by possibly two or more rooms in each apartment and the number of new apartments to be constructed in the United States and the total becomes somewhat alarming. The procedure is simple but the multiplicity of the number of measurements required makes the concept of field measurement for building code enforcement far from practical unless the data collection procedure is shortened. This can be done by field recording the various sound signals on magnetic tape and using sophisticated analysis equipment in the laboratory to provide the detailed frequency discriminated data. Laboratory computers can also process the mathematical calculations to arrive at the single number comparisons with the code requirements.

Magnetic tape recording of acoustical data has been the practice in aero-space noise studies for many years. Until recently, however, the equipment was so heavy, bulky and dependent upon an exterior power source that a truck or station wagon was frequently considered an essential component of this equipment. Today, the total equipment listed above -- all of it self-powered -- weighs no more than a sound level meter alone weighed about 15 years ago.

The recording procedure is also easy to learn by non-acoustically educated personnel and, with a little practice and training, becomes quite error free. A calibrator is used to record a "bench mark" signal -- usually 114 dB at 500 or 1000 Hz -- at the beginning of the magnetic tape using a standard sound level meter as a combined microphone and attenuator. The sound level meter attenuator is then adjusted in 10 dB steps so that the input noise signal is within the dynamic range of both the sound level meter and tape recorder. The operator must make an immediate notation of the change or by speaking into the microphone, record the new attenuator setting on the magnetic tape. The recording amplifier gain control of the tape recorder must not be changed during the entire procedure. If accidentally or purposely changed, the calibration signal must again be recorded.

During the past year, our firm has trained about 30 non-acousticians in the above procedure with good success. Our laboratory has reduced their recorded tapes to octave band and 1/3 octave band data using a General Radio Type 1921 Real-Time Analyzer. In all cases the frequency characteristics of each of the sound level meter-tape recorder sets was established in our laboratory before the equipment was used. The Real-Time Analyzer filter network was set to conform with the frequency characteristics of the individual recording equipment before proceeding with the data reduction.

At first, some of our people were concerned about the possibility of errors. However, improper microphone location, shielding of the microphone by the operator's body, improper loudspeaker location, and similar potential field errors were avoided by means of careful, step-by-step instruction manuals. In addition, during the training period, each operator conducted several tests of each type under the supervision of a qualified acoustical engineer.

Forgetting to make note of a reset sound level meter attenuator or noting the change incorrectly, can interject a subtle error and one that could seriously affect the data. To date we have not encountered this problem; however, it does seem possible to provide a so-called "black box" containing a precalibrated signal amplifier and two-track tape recorder with no attenuator or volume controls but only an "on-off" switch. Obviously, the dynamic range of the tape recorder would be limited to about 50 dB, however, the signal from the amplifier could be split to feed both channels of the tape recorder, the channel amplifiers set to differ by 30 dB. The receiving room levels and NC level measurements from 20 to 70 dB would be recorded on one channel and the louder source room levels -- 50 to 100 dB -- on the other channel.

To date we have not seen the need to go to this "black box" approach.

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2. Illustrations

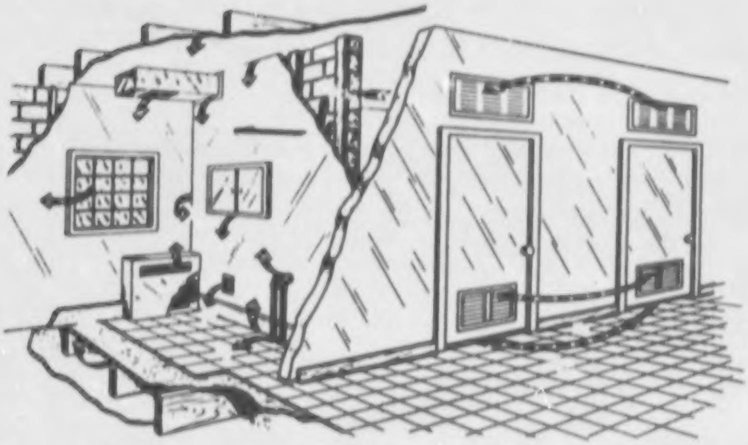

Fig. 1 From HUD, "A Guide to Airborne, Impact, and Structure Borne Noise-Control in Multifamily Dwellings"

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The Effect of Illumination Systems Upon Visual Performance

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One of the critical human factors in building design is the provision for an adequate level of visual performance, in relation to the speed and accuracy of vision. It has only recently been recognized fully that the amount of illumination on a visual task may be of secondary importance to that of another variable, the "task contrast." The concept of "Contrast Rendition Factor" will be developed, where the amount of contrast produced on a written task by any given illumination system may be evaluated in relation to a reference standard. Recent researches will be reported which indicate the ineffectiveness of present conventional illumination systems.

Further research undertaken in the development of unconventional systems of illumination will be reported, and it will be shown that a unique distribution of light within a working area can produce very substantial visual performance increases, without increasing the electrical input to the system.

Whereas the paper will include some theoretical concepts in relation to visual performance, its chief purpose will be to provide practical guidelines for the improvement of this factor.

L'un des facteurs humains critiques dans un projet de construction est la garantie d'un degré adéquat de performance visuelle quant à la rapidité et l'acuité de la vision. Ce n'est que récemment qu'on a vraiment reconnu que la quantité de la lumière dont profite un effort visuel peut être d'importance secondaire par rapport à celle d'une autre variable, "Le contraste dans l'exercice d'un effort visuel." La notion de "Facteur de production de contraste" sera mise en pratique lorsque le contraste obtenu pour un travail d'écriture avec un système d'éclairage donné pourra être évaluée par rapport à un étalon de référence. On exposera des recherches récentes qui indiquent l'inefficacité des systèmes d'éclairage conventionnel actuels.

Une étude ultérieure entreprise pour développer des systèmes d'éclairage unique sera décrite et on montrera qu'une distribution de lumière unique dans un espace où l'on travaille peut produire des accroissements notables de performance visuelle sans augmenter la consommation de courant électrique dans le système.

Bien que la communication comprenne quelques notions théoriques en rapport avec la performance visuelle, son but principal est de fournir des indications pratiques pour améliorer ce dernier facteur.

Key words: Illumination systems; lighting; performance concept; task contrast; veiling reflections; visual performance; visual task.

1. Introduction

When considering the performance concept in building design, a factor of prime importance is adequate levels of visual performance. Visual performance is a measure of the speed and accuracy of carrying out a visual task such as reading, writing, or quality inspection, and normally is taken to be a function of the illumination level maintained in the work area. In recent years, however, studies have shown visual performance may be affected greatly by factors not usually taken into account. [1,2,3,4,5,6][1]

When a person is carrying out a visual task, four primary factors affect his visual performance, namely size, time, background brightness, and contrast. In a reading task, these factors would be respectively the size of the print, the time taken to read a given amount of material, the brightness of the paper, and the brightness contrast between the paper and print. The building designer has little if any control over the task size or the viewing time, but has considerable control over the other two factors. The background brightness is a function of the quantity of illumination and the reflection characteristics of the visual task. Providing a certain illumination level will produce predictable brightness levels for materials of known reflectance. The fourth factor, task contrast, has not been considered fully in lighting design until recently. The purpose of this paper is to show the importance of task contrast as a factor affecting visual performance, and to describe recent engineering developments which allow illumination systems to be designed for increased performance by correct control of contrast.

2. The Effect of Contrast

Contrast has been defined by the following equation:

$$C = \frac{B_1 - B_2}{B_1}$$

where C is contrast, B_1 is the brightness of the background (paper in typical reading tasks), B_2 is the brightness of the information (pencil or ink in typical reading tasks).

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[1] Figures in brackets indicate literature references at the end of this paper.

This expression has been found to describe accurately the visual sensation resulting from a brightness difference between two areas.

The importance of contrast as a determining factor of visual performance will be appreciated readily; compare the ease of reading black lettering on a white background to that of reading the same lettering if printed on dark gray paper. In order to overcome the contrast difficulty in the latter case, an extremely high illumination level would be required, thereby providing increased brightness to offset the low contrast. Figure 1 indicates how variation of task contrast requires changing the brightness level in order to compensate and produce a fixed level of visual performance. This relationship, known as the Standard Performance Curve, shows that a small loss of contrast requires a very large brightness increase to retain a certain visual performance level; a 1% contrast loss will require typically a 10% to 15% brightness increase. Such an increase in brightness requires a commensurate illumination increase, which normally is not economically feasible.

Relatively large losses of contrast are caused by a phenomenon known as "veiling reflections," which are commonplace under today's typical illumination systems. Figure 2 illustrates the cause of veiling reflections. A lighting fixture in a ceiling area slightly in front of the observer will illuminate the visual task. Specular reflections will be thrown into the observer's eyes, reflected from the glossy portions of the task. Pencil handwriting, for instance, will reflect such light so that the pencil lines will increase in brightness, and therefore the contrast between the lettering and the diffuse white paper will decrease. Figure 3 illustrates a task illuminated under conditions condusive to high contrast rendition, while figure 4 shows the same task as affected by veiling reflections.

When loss of contrast is great, as when a light source is reflected from a glossy magazine, a person will compensate by moving his location or that of the magazine. However, the human eye does not always recognize consciously the subtle small losses in contrast, even though these may be highly significant in visual performance, resulting in loss of visual accuracy or slower performance.

As we cannot economically or technically justify the extremely high illumination levels required to overcome contrast losses, we can conclude that serious visual performance deficiencies are being experienced under conventional illumination systems due to veiling reflections.

3. Evaluation of Contrast Loss

A technique of evaluating lighting systems has been developed, based upon the contrast and visual performance they produce. "Contrast Rendition Factor," CRF, is the ratio of the contrast which a lighting system produces on a standard reference pencil task to the contrast produced on the same task when illuminated by a fixed reference lighting system. The reference lighting system is an integrating sphere, which is painted on the inside with a white diffusing paint,with the reference visual task at its center, figure 5. Light is beamed into the sphere and strikes a diffusing cone, whereupon multiple reflections inside the sphere ensure total diffusion of the light. A lighting system which produces the same task contrast as the sphere will have a CRF of 1.000.

Contrast is measured by a Visual Task Photometer, an instrument which essentially determines the brightness of the task object and that of the background, under both sphere and normal environment conditions.

The contrast produced by the sphere is relatively high. Let us suppose that an illumination level of 100 footcandles (1080 lux) is required to provide a given level of visual performance. Under a conventional lighting system, this level will have to be increased, let us say to 120 footcandles, (1290 lux) to maintain the same level of visual performance, due to contrast losses caused by veiling reflections. On the basis of visual performance, therefore, 120 fc. (1290 lux) of conventional lighting in this example are equivalent to 100 footcandles (1080 lux) of sphere illumination. We would state therefore that the conventional system provides an "Equivalent Sphere Illumination" of 100 footcandles (1080 lux). Equivalent Sphere Illumination, or ESI, is used as the common standard of comparison between lighting systems, as it represents a measure of the level of visual performance that the system will produce under the given measurement conditions.

The ESI level may be determined from the values of task illumination, task brightness, and Contrast Rendition Factor. [6]

4. Control of Contrast Losses

The losses of contrast caused by conventional lighting systems have been well documented. [1,2,3,4,5,6] As an example, a study in the Toronto School System showed that contrast losses due to veiling reflections of 21%, 17%, and 11% for typical pencil written task occurred under a louvered lighting system, a general diffuse system, and an indirect system respectively. Subsequently, a study at Southern Methodist University showed that illumination coming predominately from the side was capable of creating high levels of contrast due to the effect shown by figure 6. [4] Specular reflections are cast away from the eye rather than towards the eye. As a result of these and other studies, lighting systems were designed to produce a light distribution as shown in figure 7. Very little light is directed downwards, while the major emission occurs in twin beams on each side of the fixture at angles of about 30°.

As shown by figure 7, rows of "Twin-Beam" fixtures can be arranged so as to have overlapping light patterns. A person seated beneath a row of fixtures will receive much more light from the side than from fixtures above his head. In this way, his source of veiling reflections is removed, yet adequate illumination is maintained due to the light incident from the adjacent rows. Measurement of the CRF values for several conventional lighting systems and the Twin-Beam system has shown that the CRF losses associated with conventional equipment are eliminated, and a uniformly high level of contrast maintained under Twin-Beam systems. [5,7] An analysis has been conducted of four lighting systems having conventional candlepower distributions as shown in figure 8 and a Twin-Beam distribution as shown in figure 9. A lighting system using each type of distribution was installed in the Illumination Systems Research Laboratory consisting of a room 24' X 32' X 9'. The wall reflectance was .65, the ceiling .80, and the floor .21. Each system had 42 lamps and power consumption of approximately 2100 watts.

Measurement of CRF and calculation of the ESI level showed that the Narrow distribution system, using recessed louvered units, produced a minimum of 32 ESI footcandles, (340 ESI lux). The Medium distribution system, recessed units with a diffuser, gave a minimum of 47 ESI footcandles, (510 ESI lux), while the Wide distribution fixtures, which were surface attached units with luminous sidewalls, gave a minimum of 58 ESI footcandles, (620 ESI lux). The Twin-Beam system using single lamp surface attached luminous sidewall luminaires produced a minimum of 104 ESI footcandles, (1120 ESI lux). Thus the efficiency of the Twin-Beam system can be seen to be very much higher than that of the conventional systems, when evaluated on a true performance basis.

5. Financial Evaluation of Lighting Systems

The ultimate index for evaluating the visual performance of various lighting systems must be the value of the performance to the occupant. Reducing all significant costs to a cost index and using a time/value-of-money concept permits a performance evaluation based on the annual cost per ESI footcandle over the life cycle of the building.

The first cost of each lighting system described above is given in column 5 of table 1, and is based upon the trade price for the fixtures and the installation costs. The total annual cost of each system is given in column 9 with Capital Recovery based on 10% interest and a life of 15 years on the fixtures. A 2.5 cent per KWH rate has been used to estimate the power costs.

The annual cost per ESI footcandle is given in column 10, and it can be seen that the Twin-Beam system of illumination is substantially cheaper than all three conventional systems when evaluated on the basis of the performance it produces. Factors comparing the cost of the various systems to that of the cheapest are given in column 11.

Using the traditional methods of cost evaluation based upon conventional illumination levels, rather than performance and the ESI concept, would provide a totally different cost comparison. On such a basis, the wide distribution system would be selected as the most economical. As we know, however, although the wide distribution system would deliver the highest illumination level, it would produce only approximately half the ESI level, and therefore would be substantially inferior on a performance basis. Unless a valid performance criterion is used as the basis of selection, a low efficiency system will be selected in the false belief that it is the most economical. Now that the technology for visual performance specification has been developed, let us use it as an illumination design criterion in the future

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Table 1. Economic Analysis of Typical Room

					Annual Costs					
Illumination System	ESI fc.	Total Fixture Cost	Instal-lation Cost	1st Cost Installed	Capital Recovery 10% 15 years	Power 2.5¢/ KWH	Maint. & Insurance	Total	Per ESI fc.	Cost Comparison Factor
Louver Narrow Beam	32	$ 630	$230	$ 860	$113	$123	$30	$266	$8.31	2.45
Diffuser Medium Beam	47	$ 730	$230	$ 960	$126	$123	$30	$279	$5.94	1.75
Surface Attached Wide Beam	58	$ 680	$175	$ 855	$112	$123	$30	$265	$4.57	1.35
Twin Beam	104	$1050	$350	$1400	$184	$123	$45	$352	$3.39	1.00
1	2	3	4	5	6	7	8	9	10	11

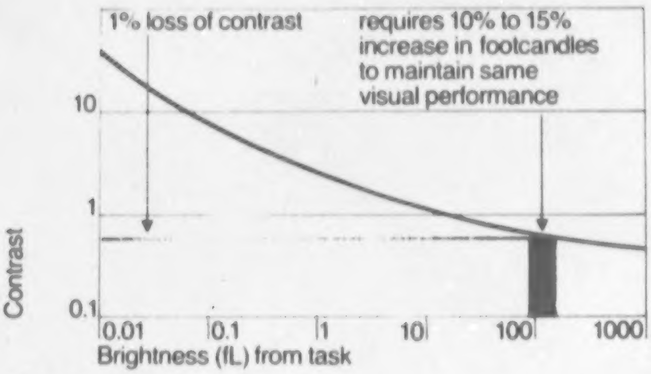


Fig. 1
Standard Visual Performance Curve

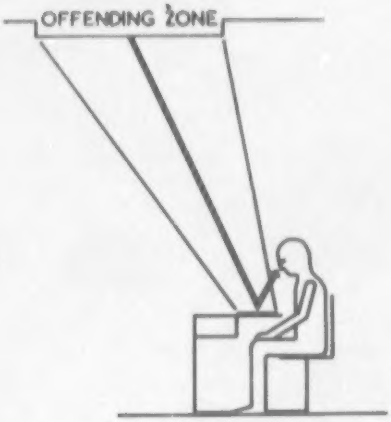
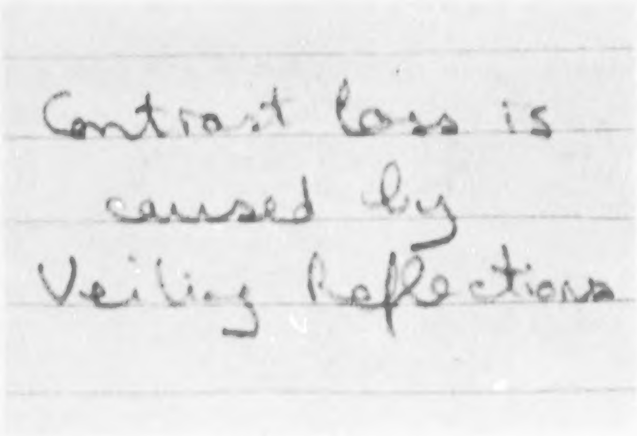
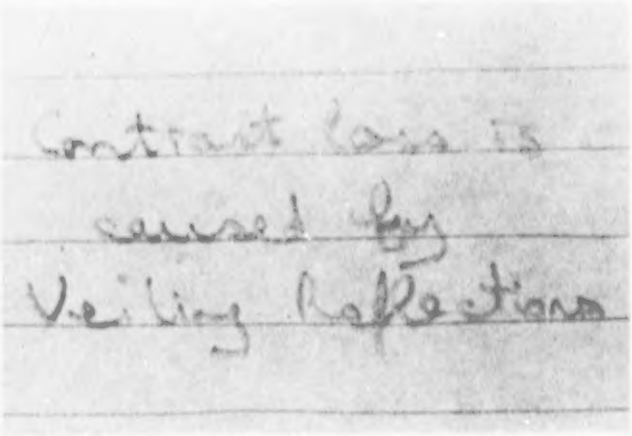


Fig. 2
The cause of veiling reflections



Contrast loss is
caused by
Veiling Reflections

Fig. 3
Pencil handwriting showing high contrast



Contrast loss is
caused by
Veiling Reflections

Fig. 4
Pencil handwriting showing contrast loss

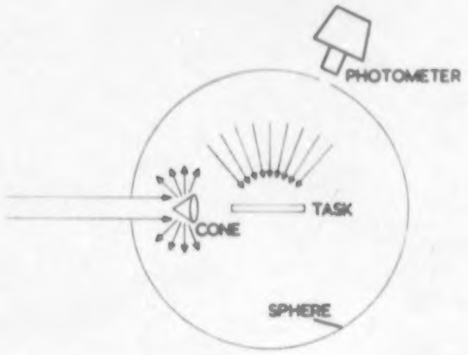


Fig. 5
Reference sphere lighting system

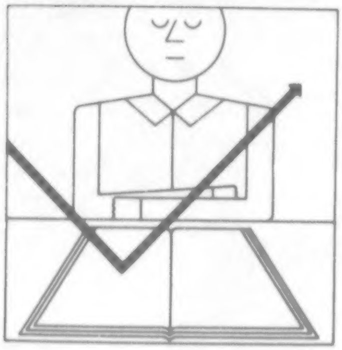


Fig. 6
Veiling reflection control by
Twin-Beam system

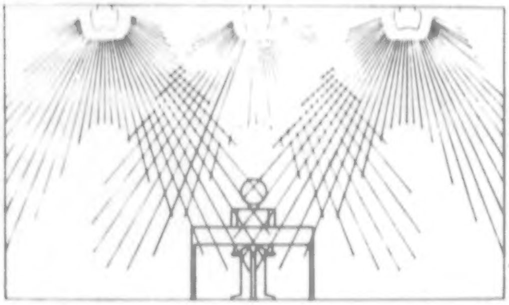


Fig. 7
Application of Twin-Beam luminaires

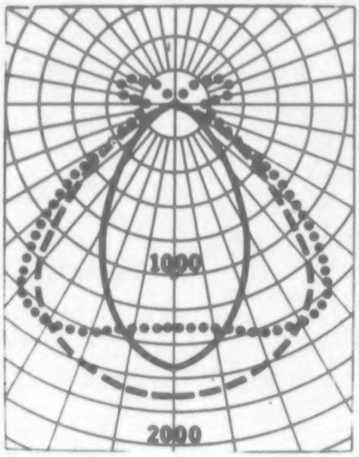


Fig. 8
Candlepower distributions of the
conventional luminaires. Across
axis plane.

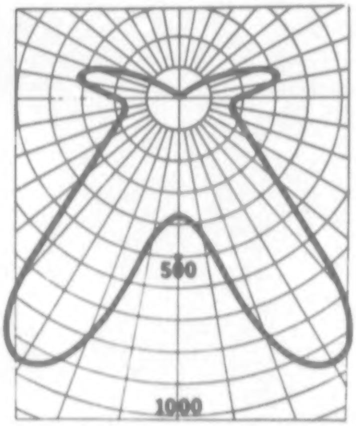


Fig. 9
Candlepower distribution of Twin-
Beam luminaires. Across axis
plane.

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

The Performance Concept in the Service of Technical Evaluations of Building Innovations

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The introduction gives a broad picture of the increasing effort of the National Building Research Institute (NBRI) in the field of technical evaluation and performance requirements. Terminology is also defined. This is followed by a section in which work on certain selected aspects of performance is discussed. The concluding sections deal generally with the performance concept and its cardinal position in the evaluation of innovations in building, and bring out some of the practical limitations of the concept and the continuing need for the exercise of evaluative judgement.

L'introduction décrit dans leurs grandes lignes les efforts de l'Institut National de Recherches sur la Construction (NBRI) dans le domaine des évaluations techniques et des exigences de performance. On définit aussi la terminologie. Ensuite vient une section dans laquelle on examine le travail accompli sur certains aspects déterminés de la notion de performance. En conclusion, on traite la notion de performance en général et son caractère essentiel dans l'évaluation des innovations dans la construction, et l'on fait ressortir quelques-unes des limitations pratiques du concept ainsi que la nécessité d'exercer continuellement un jugement critique.

Key words: Agrément; durability prediction; economic aspects; evaluative judgement; need for clarity of purpose; performance concept; plastics in fire; rain penetration; robustness of construction; technical evaluation; uniformity of assessment; weathering.

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1. Introduction

Much of the work of the National Building Research Institute (NBRI) is connected in one way or another with technical evaluation of buildings or their constituent parts or materials. The NBRI was established in 1945 and has steadily grown until in 1970/71 it has a staff of about 180, and a budget of about (U.S.) $2 million.

The first comprehensive statement on performance requirements and evaluations made by NBRI was embodied in a general publication on the costs of low-cost housing (1)[2] issued in 1954, the result of six or seven years of concentrated team work. From time to time thereafter the Institute undertook a comprehensive technical evaluation of a novel or unorthodox form of construction on a contract basis for a sponsor. This work built up over the years and, in order to formalize and rationalize the evaluation process and to bring it into line with overseas procedures, the Agrément Board of South Africa was established in 1969 with the NBRI as its Evaluating Agency.

The extent of the present technical evaluation work can be judged by the fact that the total governmental and private sector contributions to Agrément and non-Agrément evaluations in 1970/71 is estimated at $140 000, which is one-fourteenth of the Institute's total budget and nearly one-third of its earned income.

At the time of the creation of the Agrément Board, NBRI drew up a current 'state-of-the-art' document in which Interim Performance Criteria for use in Agrément Board work were discussed: this document has not been published, but certain of the criteria are becoming apparent in the details included in the Certificates now being issued by the Board. Some of the performance requirements will also be found in the Standard Building Regulations, Codes of Practice or Standard Specifications of the S.A. Bureau of Standards, as members of the Institute invariably sit on the committees responsible for these documents. Local authorities also seek advice on improvements in their building regulations and the NBRI's thinking on performance requirements has an effect here also.

This, briefly, is a broad picture of the Institute's role and its increasing effort in the field of technical evaluation and performance requirements.

2. Terminology Used

In order to fall into line as far as possible with the thinking of the Working Commission W60 of the Conseil International du Bâtiment pour la Recherche, l'Etude et la Documentation (CIB) on 'The performance concept' as expressed in the proposal made by the British Building Research Station to the September 1971 meeting of W60, the following terminology is used. Simple examples are given to make the meaning clear:

The logical steps seen in establishing an evaluation process for building innovations are as follows:

1. Functional requirement Example:

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[2] Figures in brackets indicate the literature references at the end of this paper.

The external wall shall successfully resist the forces of nature, including rain, wind ...

2. Performance test

   Same example, one aspect:

   The specified sample of external wall shall be sprayed with water, with the apparatus designated, under the following conditions of duration/intensity/air pressure ....

3. Performance requirement (W60 terminology)

   or

   Performance criterion (NBRI terminology)

   Same example:

   When tested as above, the test wall shall not leak under the simulated conditions (a) and (b) for proposed use in any part of the country, but under condition (c) ....

4. Assessment or judgement (NBRI final step in evaluative process).

3. Some aspects of work at NBRI on performance requirements

3.1. Rain penetration

Much of the early work was on developing performance requirements and a testing technique in respect of rain penetration through walls constructed of traditional materials, viz masonry. In other words the criteria were developed for walls of a more or less homogeneous nature, built of pervious elements. A consolidated report (2) was issued in 1957.

Recently another important report on this subject has been published (3) in which details are given of performance criteria on rain penetration of structures where the elements may be impervious and the joints become all important, such as curtain walls with windows.

Whereas in the earlier work a simple, unpressurized rain-spray box was used for testing purposes, the present approach is more sophisticated. The rain-spray test is now done on the basis of (i) a non-pressurized test, (ii) a series of pressurized tests to simulate rain accompanied by wind pressures equivalent to various wind velocities that are experienced frequently in practice, (iii) a final pressurized test to simulate conditions of simultaneous rain and wind pressure that occur infrequently in practice.

In all these tests a pulsating pressure is used as this has been shown to have an important bearing on the performance of a window, for example. It has become apparent that in the present approach there is more need for experience in the interpretation of the results obtained, or more scope for evaluative judgement.

An apparatus is at present under construction, initially for research purposes, which will be a modified form of rain apparatus in use at the Centre Scientifique et Technique du Bâtiment (CSTB) in Paris, but includes the essential aspects that allow the reproduction of the effects of the direction of air currents and pulsating pressures on a window, wall, or combined window/wall specimen.

3.2. Weathering and Durability Prediction Problems

Correlation of artificial and natural weathering conditions has always been only a partially resolved problem and one bedevilling the difficult task of predicting the durability of materials.

Considering for the moment, however, only predictions of behaviour from an inspection of samples subjected to natural weathering conditions, the NBRI has for many years had weathering stations in selected parts of the country where samples are exposed not only for domestic work but also on behalf of overseas research bodies. These stations have been selected on the basis that they are located in areas which have very different climatological parameters. The comparison of results has been hampered by the lack of scientific knowledge as to how the conditions at these stations differ from each other. With the increase in technical evaluation work and the advent of a formal agrément body, there has been increased pressure for a more scientific basis for this work. For this reason arrangements have been made to equip four stations with automatic measuring and recording equipment for total solar radiation energy, ultra-violet radiation, and time-of-wetness of specimens. At the Pretoria station, instruments will also measure the visible light and the near infra-red components of sunlight. In addition, a detailed study of temperature conditions, including surface and sub-surface temperatures of plastic materials of different colours will be carried out. The temperature survey is in itself a project of some magnitude. It should be pointed out that the results of weathering tests obtained in other parts of the world are not necessarily directly applicable to South African conditions since the importance of the various factors in the degradation process is not known except in a qualitative way. It is therefore necessary that quantitative information on these parameters be obtained and correlated with observed degradation rates.

3.3. Behaviour of Plastics in Fire

Due to the increasing use of plastics in industrialized and other forms of building, a problem has arisen of assessing the potential increased hazard to life posed by these materials in case of fire.

Before the broader aspects of this assessment can be tackled it is essential to know more about the behaviour of such materials under controlled combustion conditions. One approach that is being followed is the use of the ASTM 2863-70 oxygen-index test. This is a comparatively new test which it is hoped will provide a preliminary screening of materials into various meaningful categories of combustion.

3.4. Degree of Robustness Required of a Construction

In carrying out evaluations of partitions or building systems, attention has always been paid to the matter of resistance to impact forces that may occur in practice, paying particular attention to this in cases where thin cladding materials over a framework have been proposed as the internal or external wall construction of a building.

In Agrément work this aspect is also considered. The various building regulations of the local authorities in South Africa, however, have never included anything specific on this subject, probably because the masonry walls traditionally used were always considered to be sufficiently robust in the thicknesses specified by the regulations, and new materials and methods of construction were generally not provided for.

The NBRI performance requirements for impact resistance were incorporated in the Standard Building Regulations of the South African Bureau of Standards in the period 1959-1960, but these regulations only become obligatory in an area if the appropriate authority officially adopts them.

The first performance requirements recommended for the interpretation of the sandbag impact test had the effect of failing ½-inch-thick gypsum plasterboard, and as this material had been used extensively overseas for many years it was later felt that the requirements might be unduly conservative. A number of houses, offices, and hotels were therefore inspected in which both the ½-inch and the ⅜-inch-thick material had been used for periods of up to three years and discussions were held with overseas authorities; as a result, the criterion of height of swing of the sandbag was modified to allow the use of ½-inch gypsum board on a frame with studs at 18-inch centres but not at 24-inch centres, and to disallow ⅜-inch board at 18-inch centres. Details of the field inspections and considerations of the various aspects of performance have been published (4).

Currently research is in progress to see whether or not a change should be made from a leather bag to a cloth bag, as favoured by several of the European countries. The team concerned has also decided in principle, and for the sake of greater international uniformity, to change from a weight of bag of 60 lbs (27,22 kg) to 30 kg, which is the weight used in Europe. Quite early in the work, the use of a 4 lb (1,81 kg) steel impact tool with a chisel-like edge was also developed. The use of this has been continued to the present day because it is believed that it represents a better approach to a performance test than the small-weight steel spheres being used in Europe, i.e. it represents better the impact of sharp-edged objects such as the corner of a desk. This same point is being made in the work of CIB Commission W60.

3.5. General Remarks

The picture here is of continuous development and refinement of procedures. Experience shows that when a new material is encountered one must be ready to use judgement and modify the criteria, and this is the research approach to the Agrément and other evaluation work carried out.

This review of several parameters of behaviour indicates the nature of the Institute's activities in the field of evaluation and the development of performance requirements. It is based on international contact that keeps the Institute in touch with thoughts and trends in evaluation work and thus leads to the adoption of ideas, the adaptation of apparatus and the exchange of specimens and test results, all on the philosophy that evaluation work is essentially team work.

In South Africa technical evaluation has been closely linked with industrialized building (5), for it was the Government's desire to facilitate the rational introduction of industrialized building methods that was partly responsible for the decision to establish the Agrément Board, as a means of reassuring all concerned that any particular building system had been thoroughly assessed and was technically acceptable.

4. General Discussion on Performance Concept, Performance Tests, Criteria and Evaluations

In this part of the paper, in which the philosophy of the performance concept and its expression in performance tests and criteria is discussed, the views given are not necessarily those of the Institute's specialist workers whose subjects may be touched on for purposes of illustrating principles.

4.1. The Scope or Purpose of Evaluation Reports must be Clear to Everyone

Unless all concerned can agree internationally or nationally on the purpose of the evaluation process itself, it is unlikely that agreement on the performance concept as an aid to evaluation can be obtained. Thus, it is necessary to have clarity and agreement on the purpose of technical evaluation reports, i.e. on their scope. There are the separate or combined purposes:

(a) of obtaining clearance for an innovation by authorities who give permission to build, e.g. building regulation (code) authorities, if those authorities hesitate or refuse to allow the use of the innovation,

or

(b) of obtaining clearance by financial institutions lending money on a building incorporating the innovation, or to a manufacturer requiring finance for large scale production,

or

(c) of satisfying the client who ordered the building or his professional advisers, or both, that the innovation is technically satisfactory,

or

(d) of informing possible future purchasers of an item that it is a good product, i.e. boosting turnover and sales.

Coupled with the motives (a) to (d) above would probably be some desire on the part of the producer to obtain an improved product. In the process of evaluation NBRI has found it necessary in more than half the cases to suggest to an applicant changes that will improve the technical performance of his innovation.

In the field of building regulations a trend has been noted, not only towards greater uniformity, but also towards coverage of more items of building (6). Thus it appears that there is a trend to deal with more than mere basic safety (structural and fire safety) and health which, in the past, has been reckoned as the only justifiable basis for a restraint on a private entrepreneur in a number of western countries.

It seems that the main reason for increased interest in technical evaluation in western countries is for purposes of clearance by building regulation authorities (certainly this is the case in South Africa); thus evaluations should reflect or anticipate the trend in building regulations, and hence cover more than basic safety and health, i.e. they should attempt to give guidance on the question of whether an innovation is a 'good' one. The South African Agrément Board already appears to be set on such a course, which seems natural, in the sense that it has been conscious of the fact that it issues certificates aimed at satisfying the purposes (a) to (d) as set out above, not merely (a), and is aware that NBRI's role in evaluation is active, not passive, and often results in an improved innovation.

Outside a few specialized circles in South Africa, however, there is little awareness of the various purposes for which Agrément Certificates may be required. It may well be necessary, therefore, to explain some of the different purposes in certain circumstances in the certificate itself. An example which comes to mind is that of thermal performance of houses with lightweight walls (e.g. timber frame), where the NBRI wishes to emphasize the importance to designers and owners of correct orientation and of reducing windows on east and west walls to an absolute minimum: it is felt, however, that for other than subeconomic housing schemes the right of a house owner exists to ignore this advice, especially if there is a good view to the east or west or he is prepared to pay extra for his thermal comfort. For this reason it might be indicated in a Certificate that advice on this aspect of thermal performance is not intended to be enforced by building control authorities.

4.2. International Uniformity is more Attainable in Test Methods than in Performance Requirements or Interpretation

This symposium will certainly accelerate international and national work on the development of a general performance statement and its elaboration from functional requirements to performance tests and from there to performance requirements and evaluation, inter alia, of the performance attained in the test.

As far as houses are concerned, it cannot be expected, with our national differences in background, culture and ways of living, that a large measure of agreement or uniformity will be achieved either in the functional requirements or in the performance requirements for interpreting tests. We should expect and be determined to reach a greater measure of unanimity regarding performance tests themselves, however. As an example, for houses consider the parameter 'degree of robustness required for an internal dividing wall or partition'. One could not expect the oriental countries, for instance with a background of constructing these walls in slender wood frame or bamboo with paper or reed covering, to reach agreement with a European-influenced country where walls were traditionally built of substantial masonry. There might be agreement on impact tests, however, that would reproduce certain aspects of performance, e.g. impact of a human body or the sharp edges of furniture on the wall, or the slamming of a door (if a hinged door is envisaged). The difficulty in uniform interpretation of such tests is apparent however - differences in size and weights of the average person, differences in types of furniture. There is another difficulty in the interpretation of whether a certain degree of damage is acceptable or not - the question of whether the wall or partition is fairly cheap and regarded as disposable, or whether it is expensive and needs to be retained and repaired.

For other types of building, however, differences should be less. High-rise buildings in steel and concrete appear to be a design solution acceptable everywhere and not needing much modification on account of national differences. Perhaps the greatest difficulty in high-rise buildings will be to obtain agreement on the functional requirements or tests and criteria concerned with combating the movement of flame, heat, smoke, and toxic gases in these buildings in case of fire. Here too it seems that unity over common test methods could be more easily achieved than the functional requirements or the assessment of risk. Even achievement of common test methods is a formidable goal, however, as the work of the ISO committee concerned with fire testing testifies, notwithstanding assistance from many research and testing organizations.

4.3. The Role of Judgement in Evaluations

The author of a recently published work (3) touched on the question of how to define the test conditions of combined wind/rain/duration for high-rise buildings. In respect of rain penetration of certain types of windows, where the water would first fill an internal channel, and not necessarily overflow, he says that it is a 'matter of opinion' as to whether this leakage should be regarded as serious.

One can see the same type of problem of subjective judgement ocurring where an external façade is protected by a screen or screen wall: at what degree of protection from the screen wall does the external wall cease to be 'external', in the sense that it no longer needs to have the resistance to rain penetration that a normal external wall would need? In an evaluation where judgement is permitted it is possible to deal with this situation, but it poses a more difficult situation for building regulations, or for any situation where a rain performance test is accompanied by rigid performance requirements for interpretation of the test results.

Another item on which evaluative judgement is essential, in agrément investigations anyway, is the matter of performance with time. Accepting that a window or wall does not leak under test, will the result be valid for the construction as built in practice in, say, ten or twenty years' time? In assessing the suitability of an external building façade, if it leaks beyond the limits of the performance requirement, it is obviously unsuitable unless amended to pass these requirements. The question still remains, however, of assessing whether, in the improved form, it may leak later on, and if so, what are the implications for maintenance or repair.

These are but three illustrations which spring to mind in the case of rain penetration, where subjective judgement of the situation is necessary in order to obtain a meaningful assessment of whether a wall, window, or wall with window has a sufficient degree of rain resistance.

It is easy to find illustrations from other aspects of performance where judgement is essential. For instance virtually all guidance on durability is a matter of judgement, aided by suitable tests wherever possible.

We can therefore say that in cases of aspects of performance where the back-up performance requirements to the performance tests are incomplete, the use of judgement improves the quality of the verdict, provided the judgement is exercised by somebody who is knowledgeable about the factors involved and can take a wise decision.

4.4. The Pass-fail Criteria giving way to Pass-negotiable-fail Assessment

It seems that one of the main advantages of the comprehensive assessment system, as against a set of rigid rules for different aspects of performance, all with set limits for pass or failure, is that one can form an overall impression of a building system or innovation and, on the overall balance of the results, give it a favourable report or otherwise.

If this is so, then one can define performance of the different facets of a technical investigation in such a way that a 'grey' area exists, between failure and definite acceptance, where a construction could be accepted if too many 'greys' did not occur. Impact resistance and rain resistance are two parameters to which this approach is particularly apt.

4.5. Should Evaluations be Purely Technical?

On the basis of an overseas tour the recommendation was recently made that economic aspects of building innovations should be taken into account when technical assessments were made. The matter was referred to the Agrément Board which, whilst sympathetic, felt that this matter was outside its functions and should not be included in the agrément procedure.

While the Institute has been aware for some years of the need for an integration of economic with technical aspects in any evaluation, it is difficult to see how the techno-economic appraisal can make the same sort of impact on the building industry of a free-enterprise economy as a purely technical one can, when it is used as a back-up service to building regulation or other building control authorities. It is considered (7) that techno-ecnomic appraisals are only practicable where the seeker of the appraisal is not forced to accept the conclusions of the 'expert assessor'.

In spite of all this, however, it remains true that no technical assessment is purely technical, i.e. technical standards are not set so high that the building industry and the country cannot afford to comply with them. In other words, economic considerations are at the back of the mind of all technical personnel engaged in establishing performance criteria for technical evaluations (3) or for building regulation purposes, or should be.

4.6. Some Performance Tests can be Misleading to the Uninitiated

With the best will in the world many performance tests are far from being a perfect reflection of a functional requirement.

In many documents such as building regulations, codes of practice and specifications, performance testsare given, together with brief performance requirements but no word about the underlying function or the need to use judgement; i.e. with reference to the section on terminology at the beginning of this paper, steps 2 and 3 are present, but steps 1 and 4 are absent.

These shortcomings are probably known to those who drew up the documents, but not to many who read them. The very specific nature of a performance test and its accompanying neatly-stated performance requirement can thus be misleading. Several examples illustrating the possibility of being mislead follow, and the difficulties of the situation are discussed:

(a) Fire Aspects

The internationally agreed upon fire resistance test is often used, in conjuction with minimum prescribed ratings, in building regulations etc., and yet there are serious reservations amongst those using this tool as to its complete applicability to a real situation where fire occurs. It is recognized that doors between compartments in a building may not always be shut and that fire, heat or smoke will spread through these, or that a window is a weak link in a wall which otherwise has good fire resistance. In both instances the potential fire resistance of a wall may not therefore be fully utilized, or used at all, when a fire breaks out.

The shortcomings of the fire rating test, or any other fire test for that matter, do not, however, stop us from utilizing them. The reason is easy to find - it is simply because there is nothing better available, and these tests do bear some relationship to performance in a building when fire breaks out.

Of course we would all like to extend these tests of components to tests of complete buildings, but this is very expensive and time-consuming and the few results that have been obtained are often not of wide applicability.

Apart from the intrinsic difficulty of dealing here with an aspect of performance that is extremely complicated, we have the added difficulty that there has been little discussion in general and therefore no consensus of opinion on step 1 as set out in the section on terminology, viz the functional requirement. How far, for example, should one go, in building regulations and evaluation reports, to minimize damage to the building itself in case of fire (it being accepted for the moment that danger to life should be minimized)?

(b) Acoustical Aspects

In laying down a performance test for sound reduction between adjoining rooms, and speaking now specifically in relation to the partition wall itself, one has a choice of specifying the performance of the partition in a test situation or specifying the performance when built into the building itself.

The latter is undoubtedly the more satisfactory approach in that the effects of flanking paths in the structure are also taken into account; it deals with the performance of the completed building, not just a component. But it is doubtful if it is as much better as it seems, for in some countries that adopt a regulation specifying the performance-in-use, a reluctance or inability to force building alterations can be seen when performance falls short of what has been specified in the regulation.

It seems therefore that with both performance tests (the laboratory situation and the in-use test) there is either some inadequacy or a glossing-over of the difficulty of enforcing the requirement.

In my view, and talking now of a technical evaluation aimed at certifying an internal walling system as such, the laboratory situation is adequate and apt for a sound reduction test. It lies with the designer of a building to utilize the walling system to the best advantage: the responsibility is his, not that of the supplier of the walling component. If one wishes to allow for some of the flanking transmission that is likely to occur in practice, one can demand a slightly higher sound reduction from the walling system itself in the laboratory test situation.

5. Conclusions

The main points made or implicit in this paper may be summarized as follows:

1. The performance concept is an essential part of the evaluation of building innovations. The concept, as such, crystallized slowly and probably took explicit form as a result of the numerous investigations undertaken in different countries into building failures, as well as the need to lay down standard specifications and building regulations.

2. The creation of the Agrément Board in South Africa with a building research organization as its Evaluating Agency has both formalized and heightened the importance of a general performance statement and the needs to improve the many performance requirements that go to make up that statement, and has made it possible to do this in a research climate.

3. The work of CIB Working Commissions W60 and W31, the RILEM Study on the connection between performance, evaluation and materials science, and ISO committees working in this field, will be invaluable and should be vigorously pursued, with coordination between the bodies concerned. Terminology needs to be agreed upon and, in the long term, efforts should be made to encourage evaluating agencies to use the same performance tests as soon as international or multinational agreement is reached on these.

4. The performance concept as such can be applied in many fields, and in the field of building it is finding increasing application in technical evaluations, building regulations and specifications.

In the field of technical evaluations it is difficult to discuss the application of the performance concept without first obtaining clarity on the purpose and scope of the technical evaluation itself, i.e. agreeing on the reason for seeking an evaluation report. Otherwise misunderstandings may arise.

Similarly when considering the performance concept in a generalized way it is necessary to warn against being too dogmatic about details, as many persons are likely to view the subject mainly in the light of their own background and interest in its application to specific spheres, e.g. specifications. It may well be that the concept will find different expressions or applications, according to the end use.

5. The essential feature of the performance concept is that it seeks a formula that describes what is required of a building, component or material, and not what it must be; i.e. it seeks to describe the performance wanted and not to specify a particular solution. This is an approach that must be fostered.

We must not delude ourselves however, that by the production of a series of internationally agreed performance tests and related specific performance requirements (criteria), we will have eliminated the need for the use of judgement based on experience in summing up the long-term behaviour of an innovation.

It should also be remembered that the appraisal or agrément services for building innovations were developed in countries that have already had the benefit of standard specifications and fairly sophisticated building regulations for many years. Technical evaluations, in the sense of a more prolonged or detailed investigation of building innovations than is apt or possible with either specifications or regulations, is therefore something for which the demand is likely to continue for many years. Building, and especially modern building with its innumerable permutations of materials and details of construction, is too complex a subject to aim at deliberately avoiding the use of judgement to decide whether or not an innovation is suitable.

6. One of the main benefits of an appraisal or agrément service is that it can view the various parameters of behaviour in the light of a 'pass/negotiable/fail' classification rather than the accepted but less flexible 'pass-fail' criteria. In this way a near failure on one parameter can be overlooked if a number of excellent performances are recorded on other parameters. It may one day be practicable to also include techno-economic appraisals within this framework.

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Technical Evaluation of Components : Agrément

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It is a problem for a builder to know whether a component presents the physical properties which are needed for it to play its part correctly in the finished whole.

Various means are available to give this proof :

- the use of science and exact physical measurements,
- the use of traditional knowledge recorded in codes of practice and standards,
- the direct proof by performance tests.

Unfortunately among the properties required is durability and often it may not be possible to test it by one of the preceding methods, because scientific knowledge may be lacking, experience does not exist for new components, and performance testing takes too long where durability is concerned. Nevertheless it is necessary to have, if not a proof, at least a judgement about the durability of new materials, components, and building systems, and if a completely logical proof is not possible, the advice of the best experts based on a broad examination and various tests is the best that can be found. Such is the Agrément procédure. People such as manufacturers, builders, and administrative authorities needing the best advice on the durability of new things, can ask for an agrément issued by a group of experts drawn from all parts of the building field, utilizing the results of measurements of natural or semi-natural tests on a full or reduced scale, and experience with short term use.

It is possible to draw up a check list of the various properties that may be required of an element in service and of the means of testing them. Some examples of such properties and tests will be given.

For the convenience of the users' of Agrément a control of the manufacture of approved products is possible and may be indicated by a mark.

An agrément procedure is used in all the Western European countries which belong to the UEAtc, and which cooperate in writing common directives for agrément and in recognizing each other's agrément certificates.

Un constructeur doit savoir si le composant qu'il se propose d'utiliser a les qualités physiques nécessaires pour jouer correctement son rôle dans le bâtiment fini.

La preuve peut être apportée par différents moyens:

- l'usage de la science appuyée sur la measure de grandeurs physiques,
- l'usage de la connaissance traditionnelle rapportée dans les codes de bonne pratique et les normes,
- La preuve directe par les éssais de performance.

Malheureusement, parmi les propriétés nécessaires il y a la durabilité et souvent il ne sera pas possible de la juger par l'une des méthodes précédente, puisqu'il peut se trouver que la connaissance scientifique fasse défaut, puisque l'expérience du passé n'existe pas pour les composants nouveaux et puis que les éssais de performance sont trop longs dès lors que la durabilité est en cause. Néanmoins, il est nécessaire d'avoir, à défaut de preuve, au moins un avis sur la durabilité des nouveaux matériaux, des composants et des systèmes de construction, et lorsqu'une preuve logiquement convaincante ne peut pas être apportée, l'avis du meilleur expert basé sur de larges enquêtes et sur des expériences variées est ce qu'on peut faire de mieux. Ce jugement c'est l'agrément. Les producteurs, les constructeurs, les autorités administratives qui ont besoin du meilleur avis sur la durabilité des nouveautés peuvent demander l'agrément à un groupe d'experts représentant tous les horizons du bâtiment, se prononçant au vu de mesures et d'éssais naturels ou semi-naturels, en grandeur ou à échelle réduite.

On peut établir la liste des propriétés qui sont exigées dans un composant et les moyens de les déterminer. Quelques exemples de ces guides de justification seront donnés.

Pour faciliter à l'utilisateur l'usage de l'agrément, un contrôle des produits bénéficiant de l'agrément est possible, les produits sont alors marqués.

La procédure de l'agrément est utilisée dans tous les pays de l'Europe de l'Ouest appartenant à l'UEATC, qui établit des directives communes pour l'agrément et assure à ses membres la réciprocité de leurs agréments.

Key words : Agrement; Assessment; durability;
New materials; new processes.

This paper is a sequel to two other papers in this Symposium, on "Building Requirements" and on "The natures of performance and evaluation for the three levels : building, components, and materials "to which the reader is referred.

The problem solved by agrément is that of providing information about the end-use suitability of a component or material, or of a method used to produce a given structural part of a building.

It is known that a structural part is required to have defined physical or material qualities so that it can play its part in the construction as a whole, and that the latter can meet the needs of the users.

It can be shown that these components, materials, and structural parts possess the necessary qualities by use of the scientific method, using precise measurements and calculations. Traditional knowledge as recorded in codes of good practice and in standards can also be used. And lastly one can use direct proof by performance tests, that is to say by observing the behaviour of the structural part under natural or semi-natural conditions.

Unfortunately one cannot quickly judge durability when dealing with components or systems which use new materials. It is the use of new materials, or innovation in the use of materials, which presents a problem; the use of old materials and systems is regulated by tradition and the specifications and codes of practice which transcribe it. The real problem in evaluations is that of innovations and it is precisely for these that one is often unable to form a judgement on durability. Durability is an essential quality of buildings, it is connected with first and maintenance cost and is a fundamental consideration in the building field.

Why cannot one have a proof of durability? It is because for a new material, such as a new polymer resin, the way in which it is degraded by radiation, hydrolysed by water, oxidized by the oxygen of the air or by ozone is generally unknown. I think that we are aware at the present time, that althrough polyvinyl chloride has been in existence for some dozens of years, we still cannot correctly describe its natural aging, and that the aging of this material poses just the problem I have stated of our practical inability to predict. This situation is connected with the fact that manufacturers and chemists don't show much interest in the durability required in building.

What then are we to do about giving an opinion on durability? We must consider that this opinion on durability certainly interests the user because the durability of the building that he is buying with his own money interests him in the highest degree. It is also of interest to the designer because of his responsibilities towards the user, and it interests manufacturers because if they had a way of affirming the durability of their materials and their products it would greatly help their sales. Selling a product of uncertain durability to the building industry is practically impossible.

Isn't the solution that all these groups interested in knowing durability should get together and agree on a judgement of durability; a fallible human assessment, modifiable but jointly accepted, of durability? Naturally this judgement will be based on all available knowledge: on reasoning, often by analogy, on scientific data as far as it is available, the early examples of actual use, observation of natural aging over periods that are still too short, etc...

This judgement, formulated jointly by the best experts based on the best experimental work, is the essence of what is called agrément.

If it is sometimes impossible to make a judgement on durability, it is also not easy for each individual to check on the other physical qualities of the material. It has been considered that it would not be reasonable to say of a component that it was durable without at the same time saying whether it was suitable from all other points of view. To pronounce a cladding panel durable if it would also allow water to pass and would not resist wind would be absurd. Agrément therefore pronounces on all aspects of the suitability for use of a component, of a method, or of a material taking them as a whole. There is a tendency at the present time, first to eliminate by a refusal of agrément or by a negative opinion, components which do not show the minimum qualities indispensable for use; secondly, to indicate the level of the physical qualities of the component when it is admissible that they are different for different uses. That is the case for thermal insulation, sound insulation, etc...

While for durability we do not have a complete foundation, for all the other properties it is possible to indicate not only the level of quality one is looking for, but the way in which it can be demonstrated: measurements, technological tests, performance tests.

The complex of qualities to be borne in mind when granting an agrément, the manner in which they are to be determined, and the levels to be attained in each appear especially in the common directives for agrément drawn up by the European Agrément Union (UEAtc). These directives are published in six languages : Dutch, English, French, German, Italian and Spanish, and they may be obtained either from the Institutes which issue the agréments or from the Secretariat of the UEATc - 4,Avenue du Recteur Poincaré, Paris I6ème.

The name of the European Agrément Union has just been mentioned. It is the Union of the European organizations which issue agréments. There are at present nine of them :

- the Agrément Board of Hemel Hempstead,
- the Bundesanstalt für Materialprüfung of Berlin
- the Centre Scientifique et Technique du Bâtiment,Paris.
- the Ratiobouw Foundation of Rotterdam,
- the Forschungsgeselschaft für Wohnen, Bauen und Planen of Vienna,
- the Institut National du Logement of Brussels,
- the Instituto Eduardo Torroja del Cemento y de la Construction of Madrid,
- the Instituto Centrale per l'Industrializzazione e la Tecnologia Edilizia of Milan,
- and the Laboratoria Nacional de Engenharia civil of Lisbon.

The role of the UEATc is on the one hand to draw up common directives for agrément, and on the other hand to ensure the validity in their country of an agrément issued in another country by the confirmation procedure.

The members of the UEAtc have issued more than a thousand agréments. And the agrément system has been working to the satisfaction of users for a long time.

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Performance Requirements in a Systematic Method for Selecting Building Materials

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The purpose of the study on "Systematic Method for Selecting Building Materials" is to establish a system or rational method for solving the problem of how to select and how to use building elements or materials. This selection system is composed of the following steps.

1) Identify the conditions concerned with the use of building elements or materials and put them in order. These conditions are named "Given Conditions"
2) Select necessary performance requirements for the buildings or components according to the "Given Conditions"
3) Transform performance requirements of the building to those of building elements or materials.
4) Evaluate performance or properties of existing building elements or materials based on the results obtained by suitable proposed methods of test, calculation, and so on.
5) Select building elements or materials by means of comparing their evaluated performance or properties with those required.

The outline of this systematic selecting method is presented putting stress on the following points.

a. Classification and arrangement of the performance requirements.
b. Selection of necessary performance requirements according to the "Given Conditions"
c. Relation and transformation between the performance requirements of different levels.

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[1] Members at present; K. Shirayama, K. Imaizumi, K. Kamimura, K. Kondo, F. Saito, T. Nireki, K. Ito, F. Tomosawa, S. Sugawara, H. Suzuki, K. Kawase, Y. Takahashi, S. Oka, Y. Mimura, M. Ito

L'objectif de l'étude de la "Méthode de Sélection Systématique de matériaux de construction" est d'établir un système ou une méthode raisonnée pour résoudre le problème de la sélection et de l'utilisation d'éléments ou de matériaux de construction. La méthode du système de sélection comprend les échelons suivants:

1) Clarifier les conditions d'utilisation d'éléments ou de matériaux de construction et les ordonner. Ces conditions sont appelées "Conditions données."
2) Sélectionner les exigences de performance nécessaires pour bâtiments ou éléments en accord avec les conditions données.
3) Transformer les exigences de performance de bâtiments en exigences de matériaux ou d'éléments de construction.
4) Evaluer la performance de propriétés d'éléments ou de matériaux de construction qui existent d'après les résultats obtenus par les méthodes appropriées proposées, méthodes d'essai, de calcul etc.
5) Sélectionner les éléments ou matériaux de construction par comparaison, avec la performance requise, de leur performance évaluée ou de leurs propriétés.

Le plan de cette méthode systématique de sélection est presenté, en insistant sur les points suivants:

a) Classification et mise en order des exigences de performance.
b) Sélection des exigences de performance nécessaires en accord avec les "conditions données."
c) Relation et transformation entre les exigences de performance de différents niveaux.

Key words: Building; classification; comparison; elements; materials; performance requirements; classification; selection.

1. Introduction

Former studies and investigations on building materials in the field of building engineering have been restricted to giving information about the properties of materials. They have failed to establish the fundamental theory for evaluating them. In this context the main purpose of this study, on the systematic selection of building materials, is put forward to develop a system or rational method for solving the problem of how to select and how to use the building elements and/or building materials based on performance concept.[1][1]

2. Outline of the Selecting System

The outline of the elements of our selection system is shown in Fig. 1 and Table 1. The selection procedure is composed of these elements and the selection is performed according to the following steps:

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[1] Figures in brackets indicate literature references at the end of this paper.

1) Decision on the type of object to be selected from the classified items shown in Table 2. At present we are dealing with only 2. 3, 2. 4 and 2. 5.

2) Identify the conditions concerned with the use of building elements or materials and put them in order. These conditions are named "Given conditions". In order to make this work easily, all the given conditions are systematically classified into five groups, and each group is further divided into ten groups as shown in Table 1.

These given conditions are needed at the stage of selecting performance requirements to be considered and at the stage of transformation of performance requirements of building to those of building elements or materials, as well as at the stage of final decision on building elements or materials to be accepted.

3) Select performance requirements for the building to be considered from the table according to the given conditions. The detail of this selecting system is shown in section 3.

4) Transform performance requirements of the building to those of building elements or materials considering the given conditions. In this stage, we can utilize the knowledge of building science and technology in the field concerned.

5) Select the existing materials or building elements which might possibly be used, refering to the given conditions, and then evaluate their performance or properties by means of appropriate methods of test, calculation, and so on. The details of these evaluation methods are discussed in a companion paper in this symposium.

6) Select suitable building elements or materials by means of comparing their observed performance or properties with those which are required. Such comparisons are classified in nine columns in Table 1.

3. List of Performance Requirements

In our selection system for building materials, the performance requirement of buildings to be considered, should be chosen from Table 3. This list is composed of one hundred kinds of requirements corresponding to a hundred sub-factors classified under ten main factors.

One example of performance requirements is shown in Table 4 with its qualitative and quantitative gradings.

4. Selection of Performance Requirements

In order to select the kinds of performance requirements required, the one hundred kinds of requirements described above are rearranged into five groups according to the five fundamental aspects used to evaluate the performance of buildings. Those are safety, with regard to the occupants and their property; health and comfort of human life; utility; durability; economy; and productivity of building.

The degree of importance (I) for a certain performance requirement should be estimated by its essential importance (I_o) as well as the probability (P) of its being required.

Both degree of essential importance (I_o) and probability of being required (P) are graded into three ranks as follows:

Example of degree of essential importance (I_0) (in case of safety)

Rank A: Requirements concerned with the danger to human life, serious injury for the human body or serious damage of the property of occupants.

Rank B: Requirements concerned with light injury to the human body or considerable damage of property of occupants.

Rank C: Requirements concerned with slight injury to the human body or some damage of property of occupants.

Degree of probability of requirement (P) for a certain performance requirement.

Rank A: Very high probability and should always be taken into account.

Rank B: Considerably high probability with recommendation that it be taken into account.

Rank C: Low probability.

The importance, (I) is ranked for each group of performance requirements concerned with a certain aspect such as safety.

The rank of probability of being required (P) could be determined by the given conditions. We found that the following given conditions had the dominant influence on rank determination.

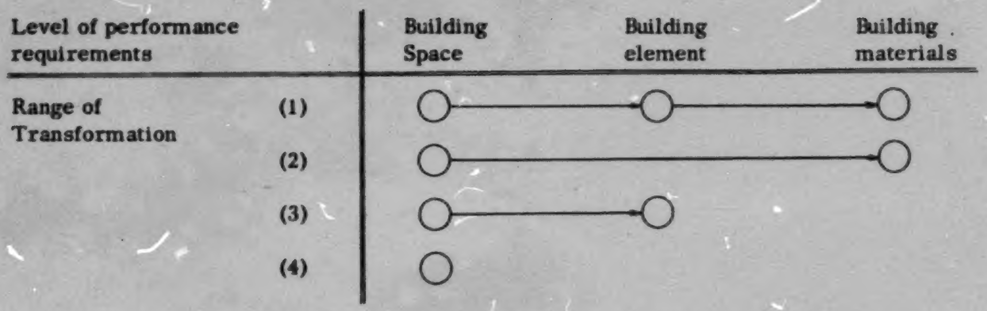
Use of building	dwelling, office, theater, etc.
Use of space	bedroom, office room etc.
Kind of building element	wall, floor, roof, etc.
Space to which building element faces	indoor, outdoor, ground, etc.
Position of material in the building element	surface, core, back, etc.

Tables for determining the rank of P according to the above conditions were proposed, and a computer programme for selecting performance requirements was developed, as a function of (I) and (P). [2][3]

The decision systems for required grade of performance requirements according to the given conditions are different from one performance requirement to another. We have already completed more than twenty of these decision systems;however,there is not sufficient space here to describe them.

5. Relation and Transformation between Performance Requirements of Different Levels

The functional requirements, once defined, are then transformed to the performance or properties required for building elements and/or building materials. This transformation is classified into the following four types.


Level of performance requirements
Building Space
Building element
Building materials
Range of Transformation
(1)
(2)
(3)
(4)

In the third type of transformation (3), the performance requirements of materials can not be deduced without considering the whole composition of the building element, and in the fourth type of transformation (4), the performance of materials or building elements can not be deduced without considering the conditions of the whole space or building.

The transformation systems differ for each performance requirement. Many of the requirements are difficult to transform with sufficient reliability because of lack of knowledge of building science.

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Table 1. System for Selecting Building Materials

	Stage					
			〔0〕	〔1〕	〔2〕	〔3〕
Given conditions	〔0〕	Conditions concerned with building site	Location	Altitude. Distance from the sea coast	Zone specified in building code	Road around the building site
	〔1〕	Conditions concerned with building	Use	Class	Expected life	Building space
	〔2〕	Conditions concerned with space in buildings	Use	Class	Expected life	Form
	〔3〕	Conditions concerned with building elements	Kind	Form	Type of structure	Expected life
	〔4〕	Conditions concerned with materials	Part of building element where material is used	Position of material in building element	Class	Expected life
Performance requirements	〔5〕	Performance requirements for buildings	Requirements concerned with external forces	Requirements concerned with water	Requirements concerned with heat	Requirements concerned with fire
	〔6〕	Properties required for building elements	Properties against external forces	Properties against water	Properties against heat	Properties against fire
	〔7〕	Properties required for materials	"	"	"	"
Selection	〔8〕	Method for evaluating of properties, material P : property possessed V : value d : property required k : constant number	Miscellaneous	Passing when $p \geq d$ rejecting when $p \leq d$	Passing when $p \leq d$ rejecting when $p \geq d$	Passing when $d_1 \geq p \geq d_2$ rejecting when $p \geq d_1$ $p \leq d_2$
	〔9〕	Method for selecting material	Miscellaneous	To select the most economical among those that meet all the requirements	To select the material which meets the largest number of requirements among those that meet the economical requirements	To select the material which meets the largest number of requirements

Table 1. (Continued)

Classification					
[4]	[5]	[6]	[7]	[8]	[9]
Earthquake Ground	Wind Storm	Rainfall, Flood	Snow	Temperature Humidity	Noise, Dust Smog
Floor space	Height	Number of stories	Type of structure	Method of operation of construction work	Period of time in operation of construction work
Area	Volume	Height	Orientation	Number of floors	Type of space adjoining
Length	Breadth, Height	Thickness	Gradient	Orientation	Type of space adjoining
Form	Length	Breadth, Height	Thickness	Orientation	Period of time in operation. Method of operation
Requirements concerned with light and electricity	Requirements concerned with sound and air	Requirements concerned with things which hit against or stick to the building	Requirements concerned with human and other living things	Requirements concerned with operation of construction work	Requirements concerned with economy
Properties concerned with light and electricity	Properties concerned with sound and air	Properties concerned with things which hit against or stick to the building element	Properties concerned with human and other living things	Properties concerned with operation of construction work	Properties concerned with economy
"	"	Properties concerned with things which hit against or stick to the material	"	"	"
$V = KP$	$V = \frac{K}{P}$	$V = f(p)$	$V = f(p)$ when $p \leq d$ rejecting when $p \geq d$	$V = f(p)$ when $p \geq d$ rejecting when $p \leq d$	$V = f(p)$ when $d_1 \geq p \geq d_2$ rejecting when $p \geq d_1$, $p \leq d_2$
Putting same weight for all property			Putting the different weight according to the property		
To select the material which has the largest sum of the value for all properties	To select the material which has the largest product of the value for all properties	To select the material which has the biggest value calculated from a function for all properties	To select the material which has the largest sum of the value for all properties	To select the material which has the largest sum of the value for all properties	To select the material which has the biggest value calculated from a function for all properties

Table 2. Classification of Objects to be Selected

1. Optimum components; optimum materials, or optimum combination of them to be used in producing components.

		(Example)
1. 1	Raw material to be used in producing components	Cement used in producing precast concrete panels
1. 2	Combination of materials to be used in producing components	Cement and fly ash used in producing precast concrete panels
1. 3	Material to be used in producing components	Concrete used in producing precast concrete panels
1. 4	Combination of materials to be used in producing components	Concrete and reinforcing steel used in producing concrete panels
1. 5	Components	Precast concrete panels

2. Optimum building elements; optimum materials and components or optimum combination of them to be used in composing building elements

		(Example)
2. 1	Raw materials to be used in producing building element	Cement to be used for masonry mortar
2. 2	Combination of raw materials to be used in producing building element	Cement and sand for masonry mortar
2. 3	Material or component to be used in producing building element	Masonry mortar
2. 4	Combination of materials and/or components to be used in producing building element	Bricks and masonry mortar
2. 5	Building element	Brick wall

3. Optimum room unit; optimum materials, components and building elements or optimum combination of them to be used in composing room unit.

4. Optimum materials, components, building elements, room units or optimum combination of them to be used in producing building.

Table 3 Factors of Performance Requirements for Building

No.	Main Factors	No.	Sub-factors
50	External forces	500	Own weight
		501	Movable load
		502	Impulsive load
		503	Vibration
		504	Seismic force
		505	Wind force
		506	Water pressure
		507	Local compressive load
		508	Earth pressure
		509	Wear
51	Water	510	Water supply and water storage
		511	Discharges
		512	Drainage
		513	Splash
		514	Outdoor moisture
		515	Indoor moisture
		516	Dew-condensation
		517	Rain water
		518	Underground water
		519	Ocean water
52	Heat	520	Solar heat
		521	Heat loss
		522	Change of room temperature
		523	Heat of heating, cooking, etc.
		524	Heat of friction
		525	Heat of industrial production
		526	Cyclic heating
		527	Low temperature
		528	Freezing and thawing
		529	Frost and heaving
53	Fire	530	Outdoor fire
		531	Outdoor flying sparks
		532	Indoor fire
		533	Interior fire
		534	Fire spread
		535	Smoke generation
		536	Fire caused by leakage current
		537	Flash over of fire
		538	Spontaneous combustion
		539	Arson
54	Light and Electricity	540	Skylight
		541	Infrared ray
		542	Ultraviolet ray
		543	Illuminating light and fluorescence
		544	Visual line
		545	Electric supply
		546	Stray current (Indirect current)
		547	Static electricity
		548	Lightning
		549	Radioactive rays (harmful)
55	Sound, Air and Gas	550	Indispensable exterior sound
		551	Dispensable exterior sound
		552	Room noise
		553	Voice
		554	Musical sound
		555	Tapping sound
		556	Amount of ventilation
		557	Air cleanliness
		558	Indoor air current
		559	Gases
56	Flying Matter, Splash Matter, and Sticking Matter	560	Dust
		561	Sticking matter (ink, paint, etc.)
		562	Oils
		563	Acids and alkalis
		564	Salts
		565	Radioactive isotope
		566	Smoke
		567	CO_2, CO and other harmful gases
		568	Filth
		569	Flying matter
57	Sense, Human, Animals and Plants	570	Form and shape
		571	Dimension
		572	Colour
		573	Touch
		574	Human feeling against action
		575	Odour
		576	Human
		577	Birds and Beasts
		578	Vermin
		579	Fungi and bacteria

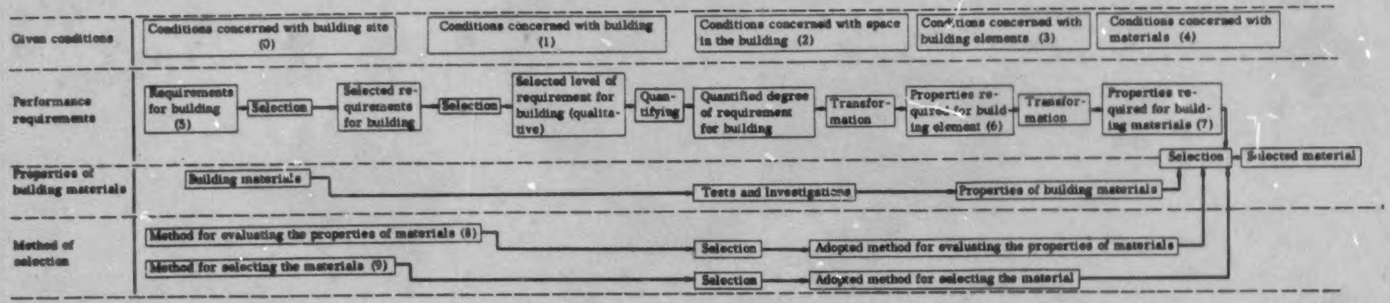
No.	Main Factors	No.	Sub-factors	No.	Main Factors	No.	Sub-factors
58	Operation of Construction Work	580	Processing	59	Economy	590	Main material cost
		581	Jointing			591	Subsidiary material cost
		582	Installation			592	Labour cost
		583	Finishing			593	Cost of construction
		584	Transportation and Conveyance			594	Procurement
		585	Module			595	Term of works
		586	Accuracy of dimension			596	Maintenance, replacement, rearrangement and reconstruction
		587	Stability			597	Life time
		588	Workability			598	Productivity
		589	Curing			599	Ultimate cost

Table 4 Example of performance requirements

(560) Dust: "Noticeability and ease of removal of sticking dust"

Grade No.	Qualitative Grading		Quantitative Grading	
	Imperceptability	Removability	Percentage of contamination: P_1 (%)	Percentage of recovery: P_2 (%)
0	Consideration of perceptability is unnecessary	Consideration of ease of removal is unnecessary	–	–
1	Fairly easy to notice	Hard to remove	$P_1 \geqq 30$	$P_2 < 70$
2		Possible to remove		$70 \leqq P_2 < 85$
3		Easy to remove		$P_2 \geqq 85$
4	Possible to notice	Hard to remove	$15 \leqq P_1 < 30$	$70 \leqq P_2 < 85$
5		Possible to remove		$85 \leqq P_2 < 90$
6		Easy to remove		$P_2 \geqq 90$
7	Not easy to notice	Hard to remove	$P_1 < 15$	$85 \leqq P_2 < 90$
8		Possible to remove		$90 \leqq P_2 < 95$
9		Easy to remove		$P_2 \geqq 95$

Fig. 1 Outline of system for selecting the building material


Given conditions
Conditions concerned with building site (0)
Conditions concerned with building (1)
Conditions concerned with space in the building (2)
Conditions concerned with building elements (3)
Conditions concerned with materials (4)
Performance requirements
Requirements for building (5)
Selection
Selected requirements for building
Selection
Selected level of requirement for building (qualitative)
Quantifying
Quantified degree of requirement for building
Transformation
Properties required for building element (6)
Transformation
Properties required for building materials (7)
Selection
Selected material
Properties of building materials
Building materials
Tests and investigations
Properties of building materials
Method of selection
Method for evaluating the properties of materials (8)
Selection
Adopted method for evaluating the properties of materials
Method for selecting the materials (9)
Selection
Adopted method for selecting the material

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

Proposed Method of Test for Evaluating Performance of Buildings, Building Elements, and Materials

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In order to select suitable building elements or materials rationally, it is essential to make clear their performance corresponding to the requirements. To achieve this, fifty standard testing methods, with evaluating methods of test results, were prepared.

These testing methods are classified into the following three groups.

a) Tests for materials (Materials-related tests)
b) Tests for building elements (Building element-related tests)
c) Tests for space or building (Space or building-related tests)

In each testing method, the following items are included.

1) Designation of testing method with its classification symbol.
2) Relevant performance requirements.
3) Scope
4) Test specimen description
5) Procedure
    5-1 Outline
    5-2 Apparatus
    5-3 Conditioning prior to test
    5-4 Details
6) Evaluation method and grade determination
7) Report
8) Notice, other relevant testing methods.

Title of all proposed methods are tabled and some of them are referred to in detail.

Pour sélectionner rationnellement les éléments et matériaux de construction convenables, il est essentiel de préciser leur performance en regard des exigences. A cette fin, on a préparé 50 méthodes d'évaluation des résultats d'essais.

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[1] Members were: K. Shirayama, K. Imaizumi, K. Kamimura, K. Kondo, F. Saito, T. Nireki, K. Ito, F. Tomosawa, S. Sugawara, H. Suzuki, K. Kawase, Y. Takahashi, S. Oka, Y. Mimura, M. Ito.

Ces méthodes d'essai sont classés dans les 3 groupes suivants:

- a) Essai des matériaux
- b) Essai des éléments de construction
- c) Analyse de l'espace ou du bâtiment

Pour chaque méthode d'essai on considère:

1) L'identification de la méthode d'essai par un symbole de classification.
2) Les exigences de performance utiles.
3) Le domaine convert.
4) L'éprouvette d'essai.
5) Le mode opératoire:
   - 5-1 Plan
   - 5-2 Appareillage
   - 5-3 Conditions antérieures à l'essai
   - 5-4 Détails
6) La méthode d'évaluation et la définition de degrés de performance.
7) Le compte rendu.
8) Commentaire et méthode d'essai appropriée.

Les titres de toutes les méthodes proposées sont classées et certaines méthodes sont décrites en détails.

Key words: Building elements; building materials; evaluation; performance; performance requirements.

1. Introduction

For the rational selection of the suitable building elements and building materials, the essential procedure is to clarify their performance corresponding to the performance requirements. [1][1]

The testing methods commonly used are not always suitable for this procedure, especially the testing methods for physical or mechanical properties and qualities of building materials.

There is a need to establish new testing methods and the new evaluation techniques to develop our system. [2]

We have endeavoured to establish the kind or testing methods and evaluation methods as a subsystem of our total system.

This paper deals with the outline of our work on proposed evaluating methods to decide the grades of the performance and/or properties for the building itself, building elements, components, and materials.

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[1] Figures in brackets indicate the literature references at end of this paper.

2. Fundamental Conception of the Testing Methods

Testing methods in this project are divided into the following three classes based on the practical application in our system.

a) Tests for materials (Material-related test)
   .... Classification number 700's
b) Tests for building elements (Building element-related test)
   .... Classification number 600's
c) Tests for space or buildings (Space or building-related test)
   .... Classification number 500's

2. 1 Material-related Tests

Material-related tests are tests to determine properties of building materials and are based on 100 required properties, called "Properties required for building materials" (details see [2]).

Most of the ordinary testing methods for building materials that have been established in the past belong in this group. However most of them serve to give the physical properties determined by procedures adapted for the convenience of measurement. Therefore it is necessary to develop new testing methods related to performance requirements.
The material-related tests are classified into the following three types as shown in Fig. 1.

2. 2 Building Element-related Tests

Building element-related tests are tests to determine performance of building elements and are based on 100 requirements called "Performance Required for Building Elements" (details see [2]).

The testing methods in this field of building engineering have become a problem of utmost importance recently, because, in general, these testing methods are more effective than material-related tests in obtaining practical information on the performance of buildings.
Some building element tests can be transfered to the building-related tests and also some of the latter are composed of material-related tests. (Fig. 2.)

2. 3 Space or Building-related Tests

In this project, space is defined as the space enclosed by building elements, for example, entrance hall and kitchen in a house, lecture room, in a school, patients room, or ward in a hospital. The building is defined as the one composed of the spaces, for example, house, school, hospital, etc.
Each test method is related to the 100 "Performance requirements for building" (details see [2]).

Corresponding to these performance requirements, therefore, at least a hundred test methods should be established; however, many of them can be performed by test methods of the 600's or 700's groups, as shown in Fig. 3.

2. 4 Outline of Proposed Testing Methods

Each description of each proposed testing method consists of the testing method itself and its explanation.

In the testing method, the following items are included.

(1) Designation of the testing method with its classification symbol
(2) Relevant performance requirements
(3) Scope
(4) Test specimens
(5) Procedure
  5-1 Outline
  5-2 Apparatus
  5-3 Conditioning prior to test
  5-4 Details
(6) Evaluating method and grade determination
(7) Report
(8) Notice, and other relevant testing methods

Classification symbols and designations of fifty proposed testing methods are shown in Table 1.

The capital T in the classification symbol stands for "Testing methods" and is added to the number of the performance requirement concerned. The number after the hyphen, shows the type of method for testing the performance corresponding to the requirements.

Details of the performance requirements, including their quantitative gradings, have already been published [1].

Example:

710T-1	Standard method of test for water absorption
7... →	Testing method for building materials
71... →	Main factor related to the requirements for building materials, "Water"
..0. →	Required property for building material, "Coefficient of absorption or rate of absorption"
...T	Test method
...-1	Number in the testing method 710

3. An Example of a Test Method

An example of the form of a proposed test method is shown in Table 2.

References

1 BRI Report, No. 51, 1968 : On the Systematic Method for Selecting Building Materials-Requirement for Building or its Part

2 BRI Report, No. 56, 1970 : On the Systematic Method for Selecting Building Materials-Standard Testing Method

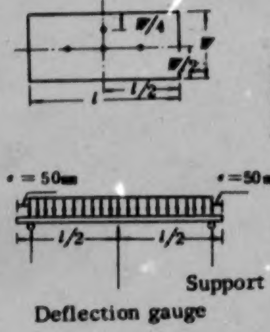
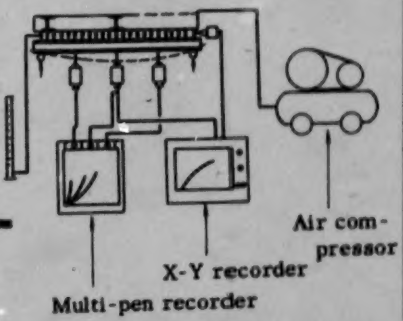
Table 1 List of Testing Methods

Classification Symbols	Testing Methods
600T—1	Standard method of test for safety factor of own weight.
601T—2	Standard method of test for resistance to bending by vertical load.
604T—1	Standard method of test for impact strength by steel ball pendulum system.
601T—1 605T—1	Standard method of test for resistance to dynamic pressure.
608T—2	Standard method of test for resistance to bending by concentrated load.
608T—1 708T—1	Standard method of test for resistance to compression by concentrated load.
768T—1	Standard method of test for wear resistance.
710T—1	Standard method of test for water absorption.
615T—1	Standard method of test for dimensional stability under water spraying.
616T—1	Standard method of test for resistance in bending as influenced by water spray.
715T—1	Standard method of test for water vapour resistance.
615T—2	Standard method of test for dimensional stability as influenced by one-sided humidity condition.
616T—2	Standard method of test for resistance to bending as influenced by humidity condition.
714T—1	Standard method of test for change of percentage of water content.
619T—1	Standard method of test for dew-condensation.
611T—1	Standard method of test for rain water penetration.
711T—1	Standard method of test for water permeability.
765T—1	Standard method of test for resistance to sea water.
625T—1	Standard method of test for dimensional stability influenced by one-sided thermal condition.
626T—1	Standard method of test for resistance to bending as influenced by one-sided thermal condition.
620T—1	Standard method of test for heat transmission.
728T—1	Standard method of test for heat resistance.
627T—1 727T—1	Standard method of test for heat resistance to cyclic aging conditions.
627T—2 727T—2	Standard method of test for resistance to freezing and thawing.
639T—1	Standard method of test for fire protection.
533T—1	Standard method of test for resistance to the growth of fire in room.
540T—1	Standard method of test for daylight factor.
743T—1	Standard method of test for resistance to ultraviolet radiation.

Classification Symbols	Testing Methods
749T—1	Standard method of test for radiation shielding.
650T—1 651T—1 652T—1	Standard method of test for sound transmission loss.
753T—1 754T—1 755T—1	Standard method of test for sound absorption coefficient.
656T—1	Standard method of test for impact sound.
556T—1	Standard method of test for rate of air change.
558T—1	Standard method of test for air flow in room.
760T—1	Standard method of test for dust contamination and decontamination.
761T—1	Standard method of test for sticking matter contamination and decontamination.
762T—1	Standard method of test for resistance to oil.
763T—1 764T—1	Standard method of test for resistance to acids and alkalis.
765T—1	Standard method of test for salt resistance.
766T—1	Standard method of test for radioactive isotope contamination and decontamination.
667T—1 677T—1	Standard method of test for damage by glass tube dropping method.
771T—1	Standard method of recommended practice for selection of agreeable color.
774T—1	Standard method of recommended practice for evaluation of agreeable touch and texture.
778T—1	Standard method of test for resistance to rodents and beasts.
779T—1	Standard method of test for resistance to vermin.
779T—2	Standard method of test for resistance to decay by fungus (poria voporaria).
682T—1 782T—1	Standard method of establishing grades for simplicity of installment.
686T—1 786T—1	Standard method of establishing grades for accuracy and adjustment of shape and dimension.
588T—1	Standard method of establishing grades for workability.
690T—1 790T—1	Standard method of calculation for estimation of construction costs.

Notice: In the classification number, 500's, 600's, and 700's numbers mean; "Buildings and Space-related Testing Method", "Building Element-related Testing Method" and "Building Material-related Testing Method" respectively.

Table 2 An example of the form of test method

(1) Designation Classification symbol		616T-1 Standard method of test for resistance to bending as influenced by water
(2) Relevant functional requirements and performance		〔513〕 Splash water 〔616〕 Change of strength as influenced by water 〔617〕 Water resistance
(3) Scope		This testing method covers the change of strength of building elements (mainly panels) as influenced by water
(4) Specimen		1. Type ; Panels for building use 2. Dimension ; 91 x 182 cm 3. Number ; Two for each type
(5) Procedure	(5-1) Outline	Sprinkle a certain amount of water on the specimen by using a sprinkler. The ratio of decreased strength to the original strength is calculated using results of strength tests obtained under uniformly distributed transverse load
	(5-2) Apparatus	1. Sprinkler 2. Apparatus for uniformly distributed transverse load for panels
	(5-3) Conditioning prior to test	20°C ± 15 deg. 65±20% RH., for more than seven days
	(5-4) Details	1. Amount of water; $4\,\ell/m^2\cdot$ min 2. Water sprinkling time; eight hours 3. Strength test; sprinkled specimen is set in the apparatus for uniformly distributed transverse load, details are shown in Fig. A and B  w/4 w w/2 l/2 l e = 50mm e = 50mm l/2 l/2 Support Deflection gauge  Fig. B Fig. A Rate of loading: $0.5\ kg/m^2/sec$

<table>
<tr><td>(6) Evaluating method</td><td>1. Visual observation; marked defects in practical use such as delamination, unusual deformation etc.
2. Strength; when the specimen is collapsed by a $\ell/150$ deformation, the strength is defined as 2/3 the breaking load, otherwise the load which makes $\ell/150$ deformation

Table 1 Grading for change of strength
<table>
<tr><td>Grade</td><td colspan="2">0</td><td colspan="2">1</td><td colspan="2">2</td><td colspan="2">3</td><td colspan="2">4</td><td colspan="2">5</td><td colspan="2">6</td><td colspan="2">7</td><td colspan="2">8</td><td colspan="2">9</td></tr>
<tr><td>Percentage of decreased strength (%)</td><td></td><td colspan="2">63</td><td colspan="2">40</td><td colspan="2">25</td><td colspan="2">16</td><td colspan="2">10</td><td colspan="2">6.3</td><td colspan="2">4</td><td colspan="2">2.5</td><td colspan="2">1.6</td><td></td></tr>
</table>
</td></tr>
<tr><td>(7) Report</td><td>1. Type of specimen
2. Drawing of specimen, dimension, section etc.
3. Temperature and humidity condition of test room
4. Load-deformation curve
Results of visual observation</td></tr>
<tr><td>(8) Notice and other relevant test methods</td><td>1. JIS-1414 (proposal)
2. ASTM-D-E72-61</td></tr>
</table>

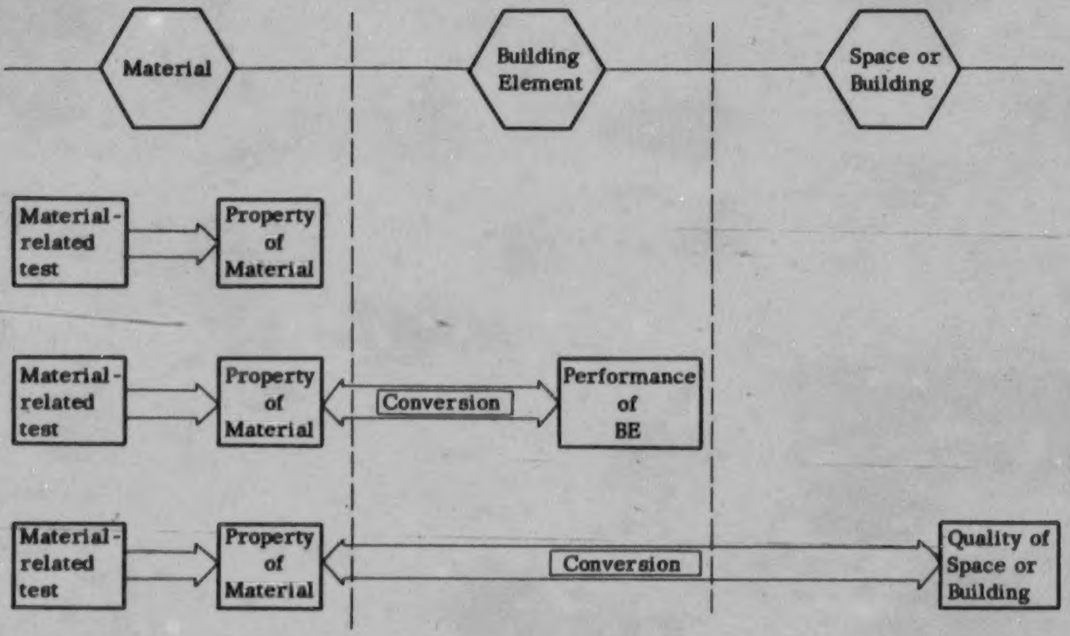

Material
Building Element
Space or Building
Material-related test
Property of Material
Material-related test
Property of Material
Conversion
Performance of BE
Material-related test
Property of Material
Conversion
Quality of Space or Building

Fig. 1 Material-related tests

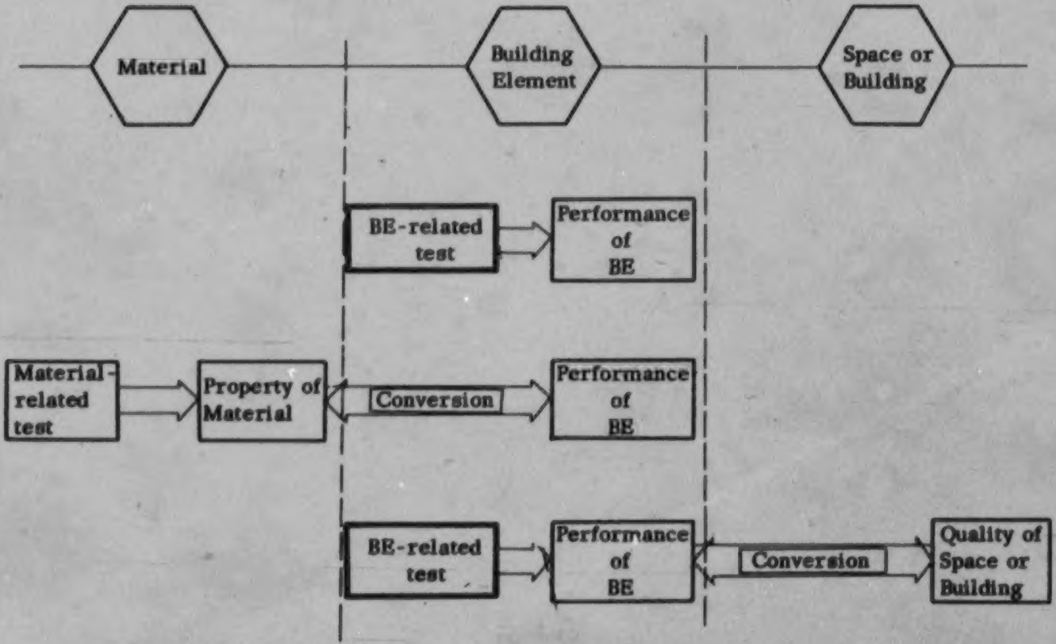

Material
Building Element
Space or Building
BE-related test
Performance of BE
Material-related test
Property of Material
Conversion
Performance of BE
BE-related test
Performance of BE
Conversion
Quality of Space or Building

Fig. 2 Building element-related tests

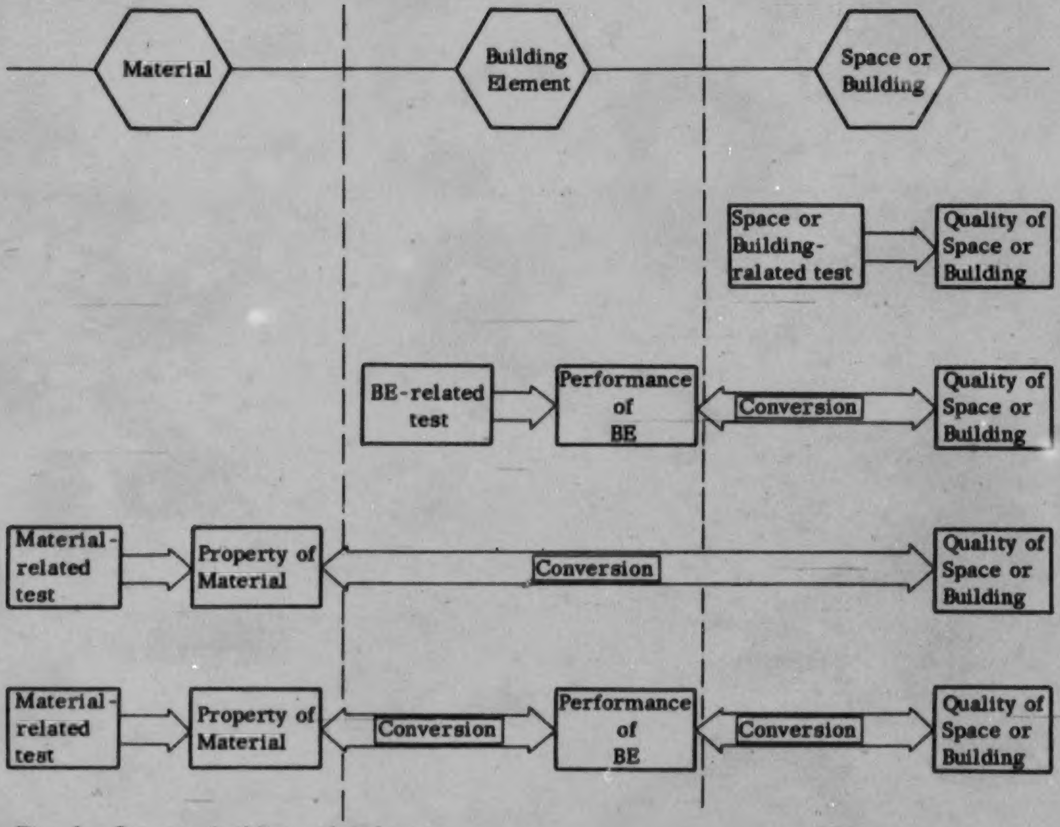

Material
Building Element
Space or Building
Space or Building-ralated test
Quality of Space or Building
BE-related test
Performance of BE
Conversion
Quality of Space or Building
Material-related test
Property of Material
Conversion
Quality of Space or Building
Material-related test
Property of Material
Conversion
Performance of BE
Conversion
Quality of Space or Building

Fig. 3 Space or building-related tests

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Performance of Components with Special Attention Paid to the Practical Implementation

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It is explained how the use of the Performance concept on the level of components has an open building system as a prerequisite and further that a number of compatibility problems thus must be solved.

Manufacturers and designers have a commen need in describing the attributes offered or required by a component on a Performance base. An example of the basic principle for such a common Performance language is shown.

The principle is used for describing the Performance attributes for bathroom walls regarding scratching resistance, ability to repel dirt, and ability to reject water spray. The background for the use of these tests is also discussed.

It is finally underlined how important it is to explain to the building industry that the Performance concept is created as an invitation to new technical solutions within building and it is not meant as a new set of restrictions to be used instead of traditional building regulations.

Dans l'utilisation du concept de performance au niveau des composants, on doit comprendre qu'il ne peut s'agir que de systèmes ouverts de construction. Ce qui veut dire que le problème de compatibilité devient particulièrement important et l'on décrit comment ceci peut être exprimé en termes de performance.

Fabriquants et projeteurs ont en commun le besoin de décrire les attributs offerts ou requis par un composant. Sur la base d'un langage de performance commun, on décrit comment un système de communication peut être développé.

Pour fournir un exemple, les exigences de performance d'une cloison sont décrites et les données de base des différentes méthodes d'évaluation sont données. En particulier, les essais pour évaluer la performance de surfaces sont décrits ainsi que les conditions requises pour l'utilisation de ces essais.

Key words: Components; dirt repelling; evaluation; feed-back; open system; performance requirement; scratch resistance; testing; water-spray repelling.

1. General approach

The basic aim of using the Performance concept within building is to promote the use of industrial methods within building in such a way that users requirements are satisfied.

Industrialization of the building process in practice can go in two directions. One direction is the development of a very limited number of closed building systems which have the advantage that the responsibility for compatibility of all subsystems within the main system rest in one place. The disadvantage of using such closed systems is mainly that it will be very difficult to meet special user requirements which fall just a little outside the capability of the system. Further a risk will exist that only a few giants will finally control the whole building industry. Such aspects are further discussed in (1).[1]

By using open systems the possibility for variety should exist if multipurpose components are produced on an industrial scale and then used by the designers for individual projects. Such an approach requires a great deal of work regarding problems in connection with compatibility between a number of components. Consequently common rules must be accepted by all involved in the design of "individual components houses" so that the component industry really gets a market for the products. In Denmark these ideas are already introduced in the Building Regulations where it is stated that all dwellings which are built for renting must be built according to the Danish rules for modular coordination.

Such rules are, however, only the first step in promoting the use of open building systems. The next and very important step will be that all components developed on a performance basis must be designed in such a way that they easily fit with other components. This means that besides performance requirements based on user needs there will exist another set of performance requirements which assure that joints between components are designed in such a way that compatibility with other products exists. In other words user performance requirement must be accompanied by performance requirements for the building process, otherwise the performance concept will not work for open building systems.

Especially for Building Research Institutes all over the world it seems to be an important task to work out general accepted rules which ensure compatibility of components in open building systems.

Most industries producing non-traditional products for the building industry must know the attributes or performance required of their product. This means that consulting engineers and architects must describe in performance terms the attributes requested and also how such attributes can be checked by means of either calculations, tests or other kind of evidence. In this connection we find the new proposal from CIB/W31-group promising as a language between the designer and the manufacturer.

When using these documents in the performance work at our institute we have developed the following approach when using this new master list in the field regarding "Behaviour in use".

General requirement

Under this heading is stated the general purpose of a certain attribute from the component in relation to user needs. Only qualitative statements are made and we believe that these statements have a fairly long lifetime, as they are to a great extent based on assumptions of user needs which do not change often.

Testing

In this part it is described how it can be checked whether the attribute in question is present. Such a method can be based on calculations, tests or even judgement. We prefer to use a kind of evidence about the attributes which do not give results of the type passed/failed.

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[1] Figures in brackets indicate the literature references at end of this paper

Evaluation

Under this heading is explained how results of testing, calculations or other methods of checking the performance could be evaluated. In most cases we propose numbers for the lowest quality we find suitable, as well as a reasonable medium level, and if possible maximum values beyond which no better performance of the product can be expected. Previously we had in our work only stated one number as "proposed degree of fulfilment", but we have found that our proposal soon was considered as a minimum requirement. We try to stress as much as possible that trade-offs between different attributes are very often a necessity in order to obtain products which also suit the user needs in an economical way.

Remarks

Under this heading is described a number of factors which do not belong naturally in the three previous parts. Very often remarks about the Building Code, Standards and so on are mentioned at this place.

After this explanation to our general approach to the performance concept it should be mentioned that in our opinion full advantage of the performance idea can only be obtained if value analysis is used as a next step. We know that this is a very difficult problem, especially when making analysis for components to open building systems, but nevertheless we feel that economical considerations have not so far been sufficiently considered. An example of the foregoing approach to the problem of performance of partitions, as proposed by the Danish Building Research Institute, is given below.

2. Some test methods

Performance specifications for partitions have already been published (2) and will consequently not be repeated here. In this connection we have always lacked test and evaluation methods for surface characteristics of partitions and other surfaces in the dwelling. This problem is very much related to the user needs as cleaning and maintenance is a problem for the user during the whole life of a building. Literature surveys have shown that today very few test methods exist which are useful to describe the surface characteristics regardless of materials. Quite a few methods exist for testing scratch resistant paints and plastic laminates, but none for surfaces in general. In the same way we have not been able to find methods which can be used to describe the ability of a surface to repel dirt or to "hide" dirt. At the Danish Building Research Institute we have started work in this field to back our general performance work, and we would be very grateful to receive information about such work in other countries. A few of the attributes of partitions regarding surface characteristics which we consider important, are described below as an example of our general approach in this field.

2.1 Resistance to scratching

General requirement

The surface should not be scratched too easily, resulting in a shabby look and/or cause expense for maintenance and repair.

Testing

For the test, a pendulum as shown in figure 1 is used. It consists of a steel rod 600 mm long with a steel load in the end. The edge of the load is formed as a parabola and has a rough edge like a file. The pendulum, including rod, load, and the special steel edge arrangement weighs 1850 g.

The surface which is going to be tested is placed in a vertical position as near to actual use conditions as possible. The load is raised to a horisontal position so that when it is released it will strike the surface under an angle of 20°. When the load strikes the surface it will swing freely out from the surface again due to the support arrangement. The strike is repeated in 10 different places on the test specimen, which for practical reasons should have a minimum dimension of 500 mm x 500 mm.

Evaluation

The scratching marks on the surface obtained from the ten strikes are compared to scratching marks in well known material surfaces. No real qualitative way of measuring the marks has been developed so far and we believe that only a grading system according to visual impression in e.g. 3 or 5 groups is possible. However, for surfaces in bath rooms we are of the opinion that the water repellant surface should not be penetrated in 9 out of 10 tests. Whether any penetration of the water repellant surface has taken place is fairly easily detected by placing the wall surface horizontally and then applying water to the surface. If the surface layer is broken and the material behind the surface is sensitive to moisture it will swell and a deformation is easily observed.

Remarks

In the Danish Building Code it is required that surfaces in bathrooms should have water repellant properties and be suited for ordinary use.

Whether this requirement is fulfilled is checked by means of the test method described.

2.2 Ability to repel dirt

General requirement

The surface should have properties such that dirt does not adhere readily to the surface. This attribute should be considered in connection with possibilities for cleaning and maintenance.

Testing

The surface in question is placed horizontally and a standard dirt is rubbed on in a specified way as a spot on the surface by means of a piece of washleather. The dirty spot, seen through a transparent film, is compared with the clean surface covered with a photographic grey scale for estimation of the level of soiling.

Evaluation

The dirty surface is placed in one of 5 classes which indicates how easily it holds dirt, which is rubbed on to the surface. The result gives a relative judgement of the surface characteristic and must be considered in connection with methods for cleaning and maintenance.

Remarks

The test method is still under development and is not yet sufficiently developed to be described in more detail. We are, at this stage, very interested in hearing if similar methods are under development in other parts of the world. We believe that such methods are of great interest for companies having cleaning as a speciality, because no method exists today by means of which the effect of cleaning can be evaluated.

2.3 Ability to repel water

General requirement

In rooms where spraying of water on the walls can be expected (bathrooms) the surface, including joints, should repel water so that materials sensitive to water behind the surface are not impaired by intruding water.

Testing

A test method simulating the exposure from a shower installation in a bathroom was developed at the Danish Building Research Institute. It consists of a shower arrangement where a number of gentle showers (with hot and cold water) spray water (5 l/min.) on all areas of the wall (including especially the joints) where leakage could be expected. In certain periods the room is dried out by means of mechanical ventilation. The test program consists of the following cycles:

1. 7½ minutes spray of hot water app. 55°C
2. 6½ " " " cold " " 10°C
3. 46 " with a high relative humidity (app. 90% RF)
4. 3 hours with drying of the room by means of mechanical ventilation with room air at the rate of app. 100 m^3/h.

The program is repeated 6 times a day and runs for six weeks. The design of the test apparatus is shown in figure 2.

Evaluation

Experience has shown that if leaks exist in bathroom walls and especially in joints there is a good chance that such leaks will be detected during the six weeks period. Such leaks are especially of importance if the wall consists of a wooden structure where rot and decay may occur. In ordinary rooms the influence of water on the walls is not considered.

Remarks

In the Danish Building Code it is required that walls around bathrooms should be made of inorganic materials or construction approved by the Ministry of Housing. The evaluation of new construction utilizing organic materials is made by the Danish Building Research Institute on behalf of the Ministry of Housing, and the result of this test method is used as a basis for a type approval.

3. Conclusion

After having worked actively to promote the performance idea for a number of years,it becomes quite evident that the final success of the idea will depend on the way the idea is introduced to the building industry. In this connection we feel that it can not be stressed too much that Performance requirements are not only used by official bodies e.g. in Building codes, but the idea applies as well to a number of attributes which are not mentioned in a building code. The advantage of using the Performance concept is quite obvious to manufacturers of new building products because it offers a very good chance to enter into a highly conservative market. In contrast to this group we find that well established manufacturers of building products very often in the beginning reject the Performance concept. However, we have found that even such manufacturers can, in the long run, see the advantage of the Performance concept, if it is clearly stated that Performance specifications are not equal to official legislation.

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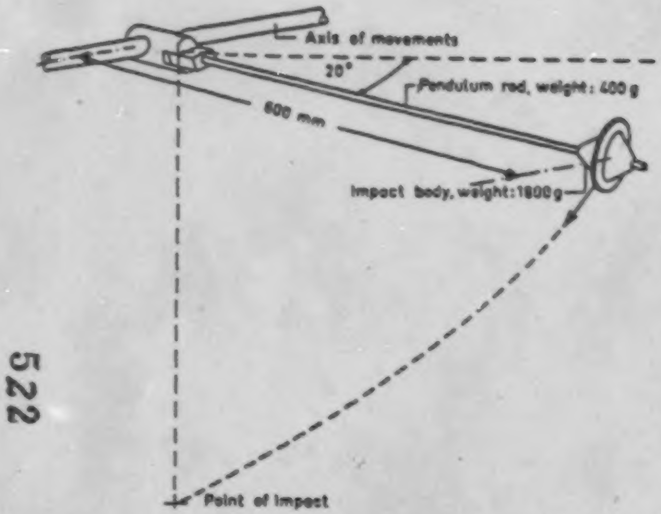
Axis of movements
20°
Pendulum rod, weight: 400 g
600 mm
Impact body, weight: 1800 g
Point of impact

Fig. 1. Instrument used for impact test on surfaces. The load strikes the surface and then swings freely away from the surface again.

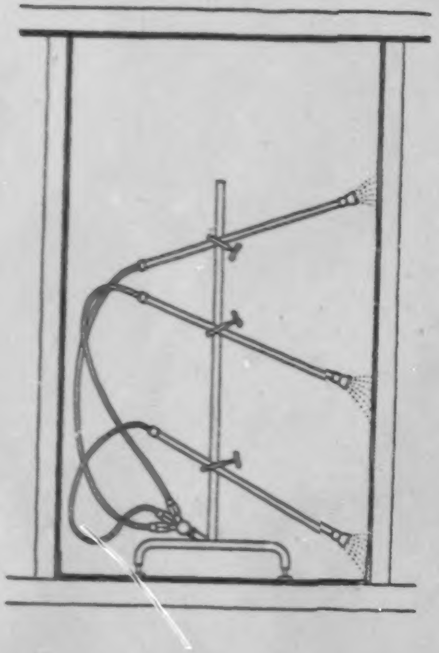

Fig. 2. Shower arrangements placed in a bathroom cabin. The gentle showers can be directed towards all connections where water leakage might occur.

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Increasing the Application Efficiency of Performance Tests with Analytic Procedures

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A method is illustrated for combining more advanced analytical procedures with performance tests of plane frame structures. A fundamental part of the method is the development of an analog, or mathematical model, of the real structure. This analog, which may be as simple or as complex as the situation warrants, is processed by a computerized system to produce a complete structural analysis. In use, performance tests of parts of the frame, particularly joints, can be used to evaluate needed parameters in the analog of the entire structure.

Three quite different examples are given showing how the analog reproduces the deformation patterns corresponding to the full-scale test structures. Acceptance of internal stresses in the analog as sufficient estimates of internal stresses in the prototype is based primarily on the deflection correspondence.

The possession of a suitable analog permits examination of a wide variety of structural variations and load cases that require verification with only a relatively small number of prototype tests.

Voici une méthode de combiner les procédures les plus avancées et analytiques avec les épreuves pratiques de charpentes plannes. Un fond de cette méthode est le développement d'un analogue, ou d'un modèle mathématique, de la vraie charpente. Cet analogue, qui devient aussi simple ou aussi compliqué que la situation le demande, est formulé par une système de computer, afin de produire une analyse complète de la charpente. Mises en pratique, les épreuves des parts de la charpente, surtout des joints, peuvent s'utiliser à évaluer les paramètres demandés dans l'analogue de la charpente entière.

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Trois exemples différents démontrent comment l'analogue réproduit des modèles de déformation conformes aux charpentes en grandes que l'on met à l'épreuve. Le principe de la correspondance des déviations donne créance au valeur des forces intérieures d'analogue comme estimation suffisante du valeur des forces intérieures de la vraie charpente.

L'analogue une fois trouvé nous permet d'examiner en théorie nombreuses charpentes et chargements dont on demande la vérification mais dont on n'a que des épreuves peu nombreuses sur les vraies charpentes.

Key words: Analysis and performance tests combined; computerized analysis; plane frame structures; test results; use of structural analogs.

The approval of a new wood frame component requires either an engineering analysis or performance tests to demonstrate its acceptability. If the component is simple, the analysis is most frequently prepared; if the component is complex, performance tests are most frequently the feasible procedure. Even though performance tests are quite costly, they provide direct and satisfactory answers. Engineering analyses of complex frames have been expensive in the past and are always subject to debate on the assumptions involved. This paper proposes a closer combination of performance testing with computerized analysis to extract the greatest amount of engineering information from the procedure at least cost.

The advantages of a greater degree of analysis are best realized through a critical appraisal of performance tests. Each test pertains only to the exact construction of the specimen. The behavior of the component, if changes are made, usually requires repeated tests until the desired objective is reached. This can indeed be an expensive process and gives cause to search for alternatives when it is realized that a computerized structural analysis is from ten to several hundred times less costly than a performance test. Furthermore, optimization is far beyond the reach of the designer using the performance test route of development, while the possession of an analytical procedure brings optimization within practical reach. Still another serious fault of performance testing lies in the specimen-to-specimen variation that causes confusion and can lead to error in comparing different styles of construction. Analytical comparisons use the same parameters, such as moduli of elasticity, in each style of component so that the resulting conclusions are based on the actual properties of the system and not on the chance values of mechanical properties of the test specimen parts.

The analytic system used herein is a computerized procedure for plane frame structures so devised as to be capable of handling almost any such structure that can be imagined. Further, the user is neither required to know how to program a computer nor is he required to master the details of matrix structural analysis. In essence, the theoretical structure consists of line or bar elements connected rigidly or with pinned ends to joint points. Any combination of uniform loads, concentrated loads, and any arrangement of reactions are possible in the theoretical frame or analog as it is called. The bar members in the analog can represent actual wood members in the prototype, or they can be used singly or in arrays to mimic the mechanical action of other structural features such as joints [1][1]. Theoretical bar elements or members of this latter type are called "fictitious members". The procedure illustrated here is one of setting up an analog to represent the prototype, evaluating missing element data by performance tests, and then comparing the deformation behavior of the analog with that of the actual component under load. Once this load-deformation correspondence is obtained between analog and prototype, it is assumed that internal stresses calculated in the analog members representing actual timbers closely approximate those in the prototype. It is also assumed that geometric variations within the limits of applicability of the fictitious members, and variations in the loading on the analog, also produce reliable estimates of deformation and stress in the new structures generated by these variations. Further verifying performance tests must, of course, be made to check the precision retained in the extremes of departure from the original structure. It is easy to visualize, however, that a few thorough performance tests of full-scale structures, along with joint tests as needed, could provide reliable verification for thousands of structural variations. It should also be remembered that the knowledge of mechanical behavior provided by the analytic system is quite detailed and complete for each variation.

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[1] Figures in brackets indicate the literature references at the end of this paper.

Valid questions can be raised concerning the acceptance of deflection correspondence as the basis for presuming correspondence of stresses between the analog and the prototype. Strain gage investigations, while a preferred approach from an academic standpoint, have not produced the precision in wood studies that has been obtained with other materials. In view of this and the extreme cost differentials between strain gage and deflection analyses, the route of qualification of the analysis by deflection data was chosen. It must also be kept firmly in mind that it is not recommended that theory be broadly applied without monitor control using well chosen experiments.

Three quite different example cases are given below to illustrate use of the method. The first example is the most recent and highly developed. The second and third are exhibited mainly to show the scope of application. Necessary limitations on the length of documentation prevents sufficient discussion here to clearly communicate the details of the analytic system and its use. This paper focuses on the consequences of use and potential application. The reference list supplies background detail including the computer program and instructions for its use.

Figure 1 shows a twelve foot span (3.66 m) King-Post truss used to demonstrate one possible technique. Two independent loadings are used to provide stronger verification of the reliability of the analog. This analog was quantitatively evaluated through performance tests of its parts and then its precision was appraised through deformation tests of the entire structure under the two independent loadings. It should be kept in mind that this truss is not a model but a full-scale unit, dimensioned so as to provide convenience in the laboratory procedures.

/ The process begins with the construction of an analog providing the needed structural features to simulate the prototype. The degree of simulation is a matter of judgment related to the precision required and the practical capabilities expected in uniformity of materials and quality of fabrication. The analog chosen for this example, figure 2, uses a bar element for each analog wood-member that possesses the axial and bending stiffness properties of its corresponding member. The metal plate joints, consisting of the wood portion as well as the metal, are simulated as to mechanical action by special short fictitious members as shown in figure 2.

The bending modulus of elasticity was determined at six-inch intervals along each of the wood members. Prior to analysis the resulting values were averaged to provide a single figure for each member in the analog. Section dimensions completed the necessary wood member information to provide axial and bending stiffness data for the analysis. Tests were devised to evaluate the bending and axial stiffness of the fictitious members representing the mechanical action of the joints. The tests involved are pictured in figure 3. It should be noted that the heel and peak joint specimens consisted of more than the fictitious members alone and that deformations measured involved wood member parts beyond the joint. In these cases analogs of the joints were constructed consisting of the fictitious members and the wood extensions as members also. Reactions and theoretical load forces were applied to these analogs,as appropriate and deformation data obtained. Following this, the joint analogs were subjected to analyses in a series in which the fictitious member section properties were altered until the joint analog deformed in theory as the specimen deformed in the test.

An earlier step in the laboratory procedure involved loading the truss with the two load cases shown in figure 1 and obtaining data on the vertical deformation of the upper and lower chords. The truss was then cut into pieces and the joint tests described in the preceding paragraph were conducted. Once the full truss analog was completely quantified with the joint tests it was subjected to analysis with the two load cases which yielded theoretical deformations. The results, which allow comparison of theory with experiment, are shown in figures 4 and 5.

Examination of figures 4 and 5 shows that the shape of the theoretical deformation curves of the members are closely traced by the shape pattern indicated by the measurements from the full-scale tests. Further, the magnitudes of theoretical and experimental deformations compare well. This supports the acceptability of the theoretical values for force, moment, and shear within the structure, which are made available by the computer system in great detail. Theoretical values for these forces and moments as well as deformation information are either directly or indirectly available for every position on the analog structure. This means that almost any design question can be answered once a suitable analog is generated for the structure in question.

Another important feature that deserves recognition at this point is that the possession of a sufficient analog now opens the door to quick, low-cost investigation of other load cases, other spans and, within limits, other slopes without further performance tests. Also, analyses can be made to predict the behavior of the truss on more than two supports and/or with the supports located elsewhere than where originally placed. This flexibility opens the way to optimization of the design within practical cost limitations.

A second example of the application of the system is introduced by examination of figure 6. This frame was developed to provide attic storage in residential construction if supported centrally in a region within 2-½ feet (.76 m) of the span center [2, 3]. The initial designs were worked out using the computer system with an approximating analog incorporating estimates of the behavior of its parts including the fictitious member arrays representing the nail-glued joints. After a proposed design was developed through the analytic route, prototype structures were built and subjected to full-scale performance tests. These showed complete conformance with strength and deformation requirements. One frame, that shown in figure 6, was subjected to particularly intensive tests that yielded complete deformation data along the lower chord. The comparisons of theory with experimental results are shown in figure 6 for both two-support and three-support cases. During the experimentation it was discovered that the central test support compressed proportionally more than the other two. The analog was accordingly modified with the addition of a fictitious member between the frame and the inner reaction. This member was proportioned to permit the analog to mimic the effect of the sinking support. After completion of the full-scale tests, the frame was disassembled to determine bending moduli of elasticity in the members, and joint load-deformation tests were run on similar but not identical specimens to evaluate fictitious members that simulated the extension characteristics of chord splices. Other joint characteristics, such as the properties of fictitious members representing the heel, were given final adjustment to fit the two-support theoretical deflection curve to the data. This means that the three-support curve and associated test data, shown in figure 6, provide an independent appraisal of the suitability of the analog. The shape and magnitude of the deflection data, when compared, show that the analog reasonably approximates the prototype. This analog is, therefore, now available for prediction of performance of other design variations and loadings.

The third example, figure 7, concerned a structure quite different from either of the preceding two. A Vierendeel type wood beam consisting of laminated chords and plywood webbed sections was attached to vertical steel columns with bolted connections [4]. Although a full-scale load test to destruction was completed prior to any attempts at analysis using the analog system described here, the data taken were sufficiently complete to allow the construction of an appropriate analog. The moduli of elasticity of the chords had been determined prior to fabrication, movement of the bolts during the load test had been measured, and lateral movement of the side columns had also been measured. These items of information were consumed in evaluating the fictitious members in the analog developed, leaving three deflection measurements in the mid portion of the span to test the quality of the analog. Comparison of the theoretical deflection curves with the observed test deflections in figure 7 shows that the analog development process had again been successful.

The degree of precision obtainable in the three displayed examples indicates the feasibility of analog development on a practical basis.

Possession of the analog allows exploration of a wide variety of alternatives without requiring performance tests of each. When applicable, optimum design can be pursued with the computer bearing the greatest share of the work.

The analog for many structural forms can be synthesized from tests of parts which, in themselves, are subjected to simple analog analysis. After approaching an optimum design, the most expensive performance tests can then be confined to only one or two specimen types with high assurance of success.

As a research tool the analog system has unlimited application in the development of new structures, development of techniques for treating complex joint systems, comparative studies, and many other related investigations. Through such research more efficient materials utilization can be realized in keeping with present day concerns over the best use of the world's limited resources.

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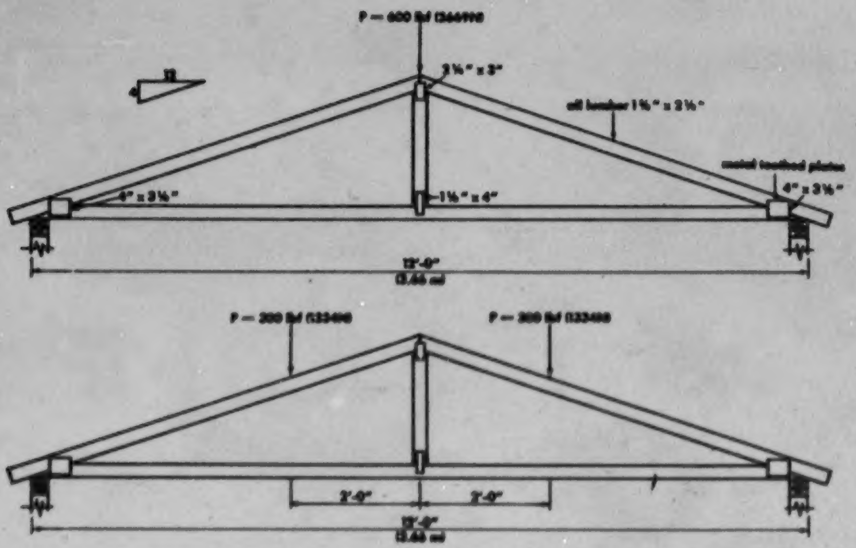
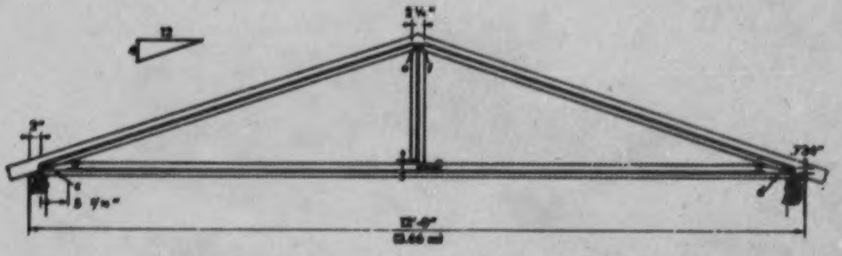
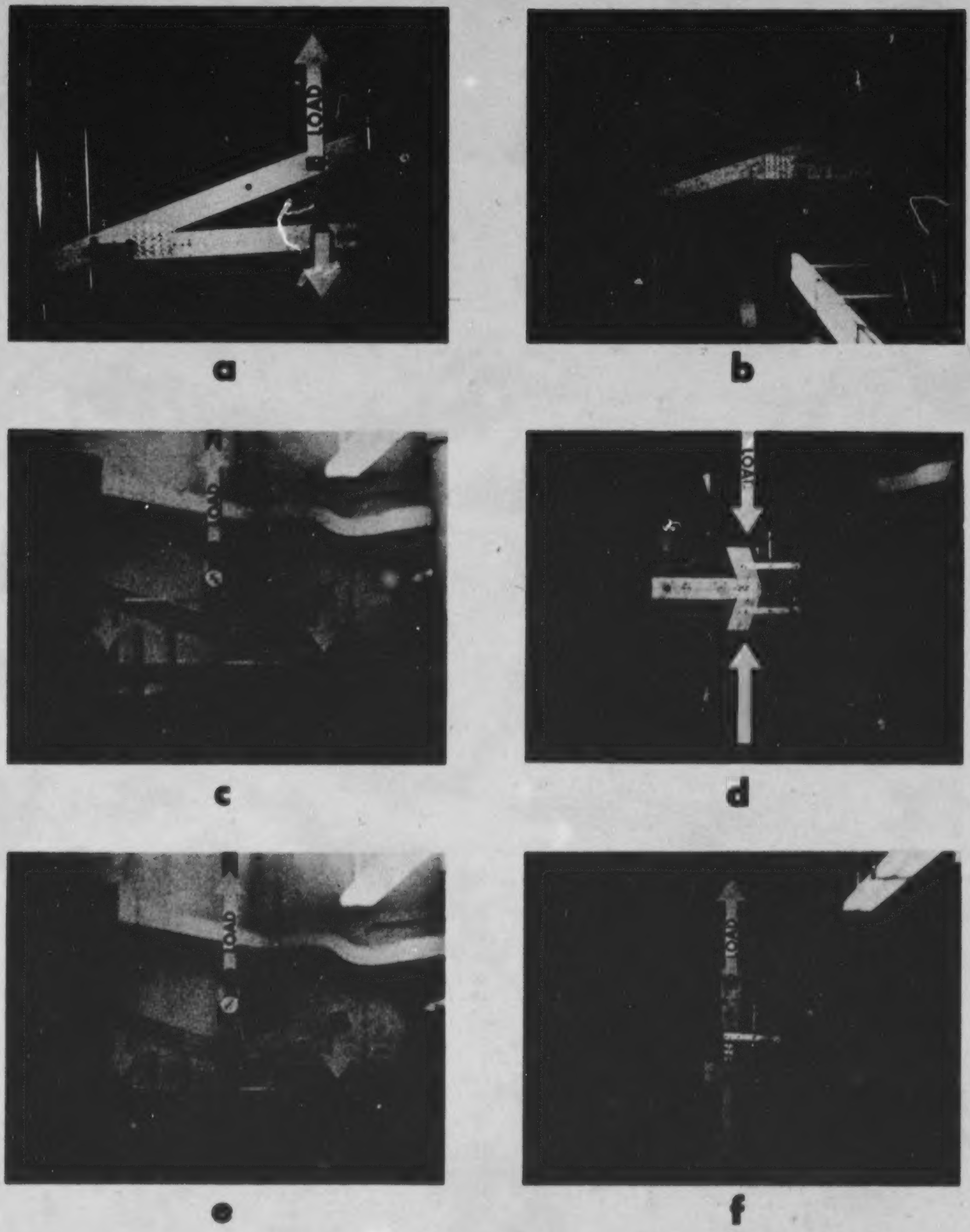

P — 600 lbf (2669N)
12
4
3¼" x 3"
all lumber 1⅜" x 2½"
metal toothed plates
4" x 3½"
1⅜" x 4"
4" x 3½"
12'-0"
(3.66 m)
P — 300 lbf (1334N)
P — 300 lbf (1334N)
2'-0"
2'-0"
12'-0"
(3.66 m)

Figure 1. A twelve foot span (3.66 m) King-Post truss with 1-3/8 inch by 2-½ inch (3.49 x 6.35 cm) Southern pine lumber and long-tooth metal connector plates is shown with the two load cases tested and subjected to theoretical analysis. This truss was treated as a full-scale structure; not as a model of a larger truss.

Figure 2. The analog or mathematical model of the truss is shown as a line structure superimposed on the prototype truss. The line members, or bars, lie along centroidal axes of the actual members. Line members a and b are fictitious members that mimic the eccentricity in the heel joints. Members c and d simulate the translational and rotational compliance of the connector and wood assemblies at the heels. Members e and f perform similar duties in the peak joint. Fictitious member g mimics the translational compliance of the upper and lower connections of the vertical post. With loads applied to it a complete theoretical analysis of the analog is available from the computer.


3¼"
12
4
e
f
3"
c
a
b
12'-0"
(3.66 m)


LOAD
LOAD
LOAD
LOAD
LOAD

a b c d e f

Figure 3. Separate tests were made on each joint which was, in itself, also modeled with an analog. These tests yielded section properties for the fictitious members shown in figure 2.

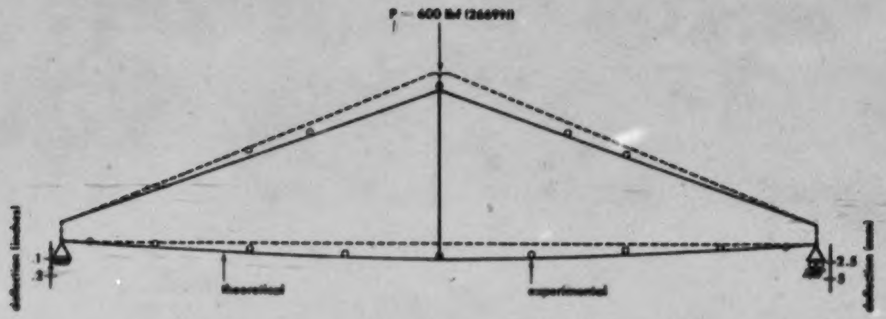
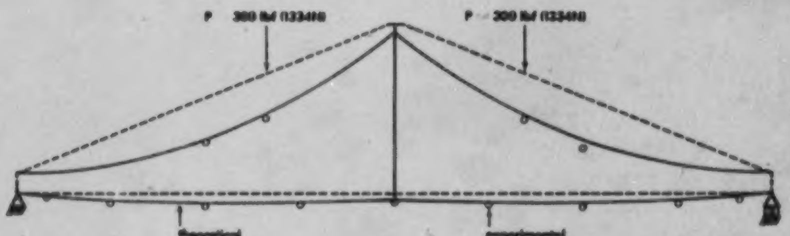

P = 600 lbf (2669N)
deflection (inches)
.1
.2
theoretical
experimental
2.5
5
deflection (mm)

Figure 4. Single concentrated load at peak joint: the theoretical deformed structure is shown in solid lines against its unloaded shape depicted in dashed lines. The dots are experimentally observed deflections plotted to the same scale of deformation.

Figure 5. Two concentrated loads at third-points of the span: the theoretical deformed structure is shown in solid lines against its unloaded shape depicted in dashed lines. The dots are experimentally observed deflections plotted to the same scale of deformation.


P = 300 lbf (1334N)
P = 300 lbf (1334N)
theoretical
experimental

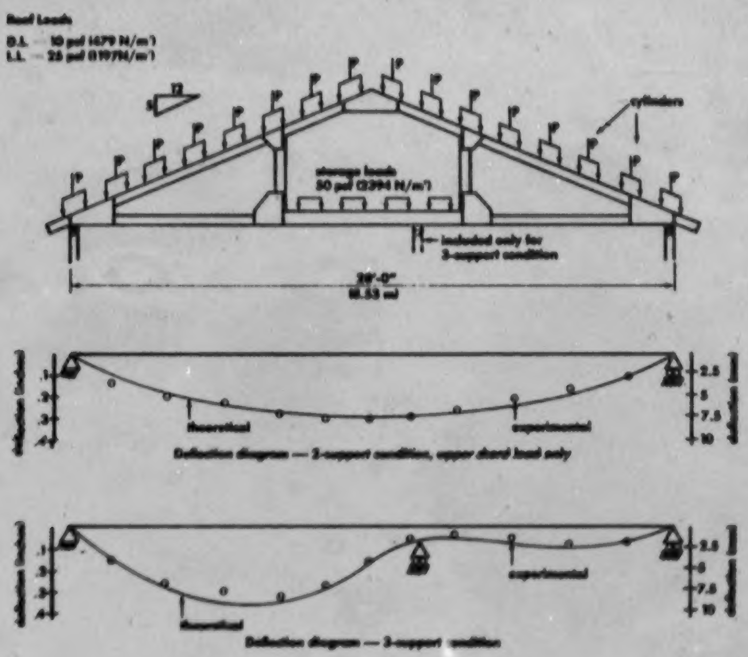
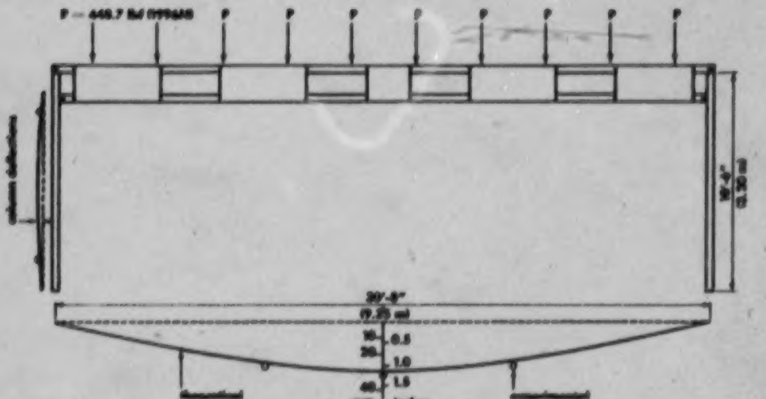

Roof Loads
D.L. — 10 psf (479 N/m²)
L.L. — 25 psf (1197N/m²)
12
5
P
cylinders
storage loads
50 psf (2394 N/m²)
included only for
3-support condition
28'-0"
(8.53 m)
.1
.2
.3
.4
theoretical
experimental
2.5
5
7.5
10
Deflection diagram — 2-support condition, upper chord load only
theoretical
experimental
Deflection diagram — 3-support condition

Figure 6. An attic storage frame built with nail-glued plywood joints was subjected to test loads under two different support conditions. Theoretical deflections (solid line) are compared with experimental observations (dots) for both cases. The actual interior support was not as firm as the exterior ones used in the test. The support conditions used in the analog simulated this situation.

Figure 7. A building frame consisting of steel tube side columns bolted to a Vierendeel type wood cross member was test loaded as shown. Theoretical deflection diagrams (solid lines) are shown with experimental observations (dots) to the left of and below the frame sketch.


P — 445.7 lbf (1983 N)
P
column deflection
30'-5"
(9.25 m)
10
20
40
0.5
1.0
1.5
mm
inches
theoretical
experimental

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Evaluation of Structural Concrete Members Penetrated by Service Systems

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Performance requirements for structural concrete members containing openings are defined. Both strength and serviceability are considered. Results of tests carried out by the Portland Cement Association to evaluate performance of flat plate and beam and slab floors containing embedded metal ducts and of concrete joists with holes in their webs are described.

On définit les exigences de fonctionnement des éléments de structure en béton comprenant des ouvertures. Résistance et aptitude au service sont ici examinées. Deux méthodes d'évaluation sont décrites, l'une fondée sur l'analyse, l'autre sur les essais. Ces méthodes sont illustrées par des résultats d'essais exécutés par la Portland Cement Association. En fonction de ces résultats, des recommandations spécifiques sont données pour évaluer la performance de plaques, de poutres plates et de dalles renfermant des conduites de métal noyées, ainsi que de solives à âme percée.

Key words: Analysis; concrete beams; concrete plates; ducts; openings; serviceability; strength; structural performance; tests.

1. Introduction

Openings for service systems may be required in many types of structural concrete members. For example, vertical openings in floor slabs and horizontal openings in beams are used for distribution of heating, air conditioning, and plumbing systems. Ducts embedded in slabs are often used for power and communication systems. Large, doorway-sized openings may be required in walls or panels.

Designers have long been faced with the practical necessity of passing mechanical systems through concrete members. In the past, these openings have usually been kept small so that they would require only small amounts of additional reinforcement. However, to fully integrate electrical and mechanical service systems into the structural components of concrete buildings, many openings of substantial size are required.

Several early textbooks [1-3][2] on reinforced concrete design included sections on openings. Recent research on openings in slabs [4-7], reinforced concrete beams [8-11], concrete joists [12], and prestressed concrete beams [13] has provided improved methods of evaluating the strength and serviceability of concrete members containing openings.

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[2] Figures in brackets indicate the literature references at the end of this paper.

2. Structural Performance Requirements for Members with Openings

Any structural concrete member, with or without openings, must have adequate strength and must be fully serviceabile for all design functions.

2.1 Strength

Currently, the strength required of concrete members is accepted as that given by provisions contained in the ACI Building Code (ACI 318-71) [14]. These provisions require that the strength, U, provided to resist dead load, D, and live load, L, shall be at least equal to:

$$U = 1.4\,D + 1.7\,L \tag{1}$$

where U = required strength to resist design loads or their related internal moments and forces, D = dead loads, or their related internal moments and forces, and L = live loads, or their related internal moments and forces. A structural concrete member with openings must meet this requirement.

2.2 Serviceability

The principal serviceability requirement is that the long-time deflection of a member, Δ, under sustained dead load and the immediate deflection due to live load be limited to a value that will prevent unsightly appearance or damage to attached nonstructural elements. The limiting value of deflection is generally expressed as a function of the span length of the member, as given by:

$$\Delta = C\ell \tag{2}$$

where Δ = maximum deflection of member, C = fraction of span length, and ℓ = span length.

Appropriate limiting values for deflection of floor and roof members are included in the ACI Code (ACI 318-71) [14]. Under any circumstances, members whose deflection is less than $\ell/480$ are considered to be satisfactory, and members whose deflections are greater than $\ell/180$ are considered unsatisfactory. It should be recognized that provisions in the Code for computation of deflections and for minimum depth of beams and thickness of slabs when deflections are not computed are not generally applicable to members with holes.

Another serviceability requirement is that crack widths must be small enough to avoid unsightly appearance and to prevent corrosion of reinforcement. Due to uneven shrinkage around an opening, cracks may develop near corners. In addition, the change in section in the vicinity of an opening may cause cracking near the hole before flexural cracking occurs in nearby sections of the member. Lacking definitive studies, it is suggested that crack widths be limited to 0.020 in. for exterior exposure and 0.025 in. for interior exposure.

3. Evaluation of Structural Performance

Although it is generally preferable to use analytical methods to evaluate the performance of a concrete member with holes, the state of the art is not presently developed to the point where this is possible. Except for a few special cases, it is frequently necessary to rely on special tests designed to verify that the performance of the member with openings is satisfactory. The following describes methodology for both analytical and physical evaluation of perforated structural concrete members. Two selected examples of evaluation by physical tests are summarized.

3.1 Strength Analysis of Beams with Openings

Some of the types of openings that may be placed in a concrete beam are illustrated in Fig. 1. These openings may be located in regions of either positive or negative moment. This will determine whether the struts above and below the opening are in tension or compression. The element between two openings is referred to as a post.

A free-body diagram of a part of a beam that includes a section through an opening of depth H is shown in Fig. 2. When a hole with the proportions shown is used, the opening does not significantly affect the location or magnitude of the compressive force, C, and tensile force, T. Consequently, the external moment, M, seldom governs. However, since the external shear, $V = V_C + V_T$, must be carried by a substantially reduced section, the shear capacity of the struts is often a controlling factor in design.

A free-body diagram for two openings placed close together is illustrated in Fig. 3. As shown, a shear, V_p, acts on the post between the openings. This shear can be estimated as the difference between either the resultant compressive or tensile forces acting on the struts of the adjacent holes.

The system of forces acting on the struts of an opening is indeterminate to the third degree. A direct solution is difficult, and the reliability of the results is uncertain because of the need to account for the non-linear effects of flexural, shear and axial deformations.

Lorentsen [8] reduced the system to one with a single degree of indeterminancy by assuming that the tensile strut was divided into short sections by flexural cracks, and hence not able to transmit shear or moment. To verify the model, tests were carried out on four T-shaped beams. The behavior of Lorentsen's test beams was in reasonable agreement with his predictions, although he did observe that the tensile strut carried substantial shear. He concluded that holes in beams should, if possible, be kept away from inflection points, and that additional stirrups should be placed near the sides of holes.

Nasser, et al [10] suggested the following assumptions to simplify the analysis of beams with holes:

1. The top and bottom struts behave as chords of a Vierendeel panel;
2. The struts, when they are not subject to transverse loads, have contraflexure points at their mid-length;
3. The struts, when they have adequate stirrups, carry the external shear in proportion to their cross-sectional areas;
4. There is a diagonal force concentration at the corners induced by the chord shear, and its value is twice the simple shear force.

A series of rectangular beams, designed on the basis of an analysis using these assumptions, was made and tested by Nasser, et al [10]. The simply supported beams were pierced by rectangular holes, and subjected to a one or two point concentrated loading. Although the majority of their specimens failed in flexure, it was concluded that the proposed assumptions were valid for rectangular beams.

Ragan and Warwaruk [13] carried out laboratory tests on prestressed concrete beams with web openings. The results were used to design a full-size 120-ft. long prestressed T-beam with ten 8-ft. long openings separated by 2-ft. thick posts. In the design, it was assumed that the shear at a critical section containing a web opening was resisted by the upper and lower portions of the web in proportion to their cross-sectional areas. Vertical stirrup reinforcement was provided in both the tension struts and the posts.

The test beam failed under a loading which produced a moment at the centerline equivalent to 1.5 D + 1.8 L. Failure was believed to have occurred due to shear compression in the flange at the high moment side of the opening closest to the simply supported end of the member.

An extensive investigation of the effect of reinforced and unreinforced openings in the webs of continuous joists has been carried out at the laboratories of the Portland Cement Association. At the present time, the results of this investigation are only partially reported. In the phase of the investigation dealing with square openings [12], it was found that the shear could be considered to be distributed in proportion to the area of the struts until cracking occurred at the hole. Joists with vertical stirrups along the sides of the holes could carry additional load. After cracking, all of the additional applied shear was found to be carried by the strut in compression. Based on these observations, a good prediction of the strength of the joists could be made using the ultimate strength provisions of the ACI Code [14].

3.2 Testing for Performance

For many systems, it appears that the present state-of-the-art is inadequate for evaluation of performance by analytical means alone. In these instances, physical tests may be needed to show that a system meets required performance criteria.

Testing to evaluate performance will usually have to be on full-size specimens, particularly if the system being tested includes manufactured components that are embedded in a concrete member. Even if the system requires only formed penetrations in the concrete, the evaluation of the details of the reinforcement around the penetration, specifically those relating to anchorage and cracking, may require testing of large-scale specimens. Highlights of two investigations are presented that illustrate methods for evaluating structural members by physical testing.

(1) Beams containing embedded metal ducts. The use of embedded metal service ducts in concrete floors provides a highly efficient means of providing telephone, power, and signal requirements in a building. Typically, the floor may be either a flat plate or the top flange of a one- or two-way beam system.

The use of a standard duct placed transversely in the flange of a T-beam was investigated [9] by testing two specimens representing continuous beams. The two test specimens were identical except for ducts in one of the beams, and the necessary re-spacing of shear reinforcement in the vicinity of the ducts. They were made with a normal weight concrete having a design compressive strength of 3000 psi. Grade 60 reinforcement [15] was used.

Figure 4 shows the beam containing the duct after it had been tested to destruction. The load versus deflection curves for both beams were virtually identical. Furthermore, there was no significant difference in the crack patterns. It was concluded that the use of ducts in wide shallow beams similar to those tested will not significantly influence their performance.

(2) Slabs containing embedded metal ducts. When ducts are used in flat-plate floors, it is frequently convenient to locate them near the junction of the slab and the supporting column. Since this is a region of high moment and high shear, the effect of the ducts on the performance of the slab-column junction must be considered.

To evaluate the performance of flat-plate floors containing embedded ducts, 10 tests [7] were conducted on large slab-column specimens consisting of a 12-ft. 10-in. square, 8-in. thick slab and a centrally located column. One of the test specimens is shown in Fig. 5. The slabs were made with a sanded lightweight aggregate concrete and Grade 60 reinforcement [15]. They were loaded by applying downward forces along the perimeter of the slab.

Three specimens, each containing a 20-in. square column, were designed and loaded so that their capacity was dependent on the flexural strength of the slab. The capacity of 5 other specimens, each containing a 14-in. square column, was dependent on the shear strength of the slab-column junction. Two of these 5 specimens contained shearhead reinforcement. The capacity of the remaining two specimens, each containing a 20-in. square column, was dependent on the combined shear and unbalanced moment strength of the slab-column junction. For all specimens, the amount and details of the deformed bar reinforcement provided were intended to represent good standard practice.

Six of the 10 test specimens contained a two level system of both 7-1/4 x 1-3/8 in. and 3-1/8 x 1-3/8 in. metal ducts embedded in the slab. Two of these 6 were in the group of specimens whose capacity was dependent on the flexural strength of the slab, three were in the group dependent on shear strength, and one was in the group dependent on combined shear and unbalanced moment. The principal variable was the location of the duct with respect to the face of the column. Duct was located either adjacent to or twice the slab thickness from one face of the column. Lines showing the location of the duct embedded in the specimen shown in Fig. 5 are marked on the top surface of the slab.

A comparison of the edge deflections for all of the test specimens is shown in Fig. 6. The ordinate in this figure is the applied shear being transferred from the slab to the column. As indicated in the figure, the test results are compared in three groups according to the intended failure mode. The first letter of the specimen identification mark distinguishes between these groups. The second letter D indicates specimens with embedded ducts and the letter S indicates specimens containing a shearhead. Specimens AD-2 and BD-5 contained duct adjacent to the column.

It was determined from Fig. 6 and from other data obtained in the investigation that the performance of specimens containing ducts located at least twice the slab thickness from the face of the column was not significantly different from that of specimens without ducts. However, the strength of specimens containing a duct located adjacent to the column was reduced when shear was critical. It was recommended that service ducts of the size embedded in these specimens be kept at least twice the slab thickness from the face of the column. Larger ducts may need to be kept farther from the column.

A test specimen, BDS-7, containing a duct 3 in. from the end of a shearhead reinforcement was not able to carry as much load as a comparable specimen, B-4, without a shearhead. The duct apparently interfered with the manner in which the end of the shearhead picked up load. Based on this result it was recommended that ducts not be placed near the end of shearhead reinforcement.

(3) Joists containing openings. The effect of reinforced and unreinforced openings in the webs of continuous joists was investigated by tests [12] on specimens which had cross-sectional dimensions similar to those of a standard 16-in. deep joist with a 3-in. thick flange. Details of test specimens are shown in Fig. 7. Each specimen was made with lightweight aggregate concrete, having a compressive strength of 4000 psi, and Grade 60 reinforcement.

When subjected to the loading shown by the heavy arrows in Fig. 7, combinations of shear and moment that would occur between inflection points of a continuous joist framing into a supporting beam were represented. Location of the openings is indicated by the distance, X, from the center of the opening to the face of the stub representing the continuous support, and by the distance, Y, from the center of the opening to the extreme fiber in compression. Openings were always located symmetrically on each side of the center stub. The dimensions H and W are the overall height and width of the opening.

Some of the test results obtained on specimens with unreinforced openings are shown in Fig. 8. Here the ordinate, $V_u/b'd\,f'_{sp}$, is equal to the ultimate shear divided by the product of the minimum web thickness, effective depth, and splitting tensile strength of the concrete. These results indicated that:

1. Moving an opening in an unreinforced web closer than twice the web depth to a simulated continuous support increased the strength of the test specimen.
2. Moving a square opening in an unreinforced web from mid-depth toward the tension fibers did not significantly affect the strength of the specimen. However, cracking at the hole did occur at lower loads as Y was increased.
3. An unreinforced web containing a square opening of one-quarter the web depth, or a circular opening of three-eighths the web depth, did not reduce the strength of the specimen.
4. Rectangular openings of H = 4 in., W = 16 in. and H = 10 in., W = 4 in. in unreinforced webs had a comparable effect on the test specimen. In both cases, strength was reduced by about 30 percent.

Additional tests were carried out on specimens with stirrup reinforcement along the vertical sides of the opening. These test results are shown in Fig. 9. In all except two specimens, the side reinforcement consisted of a two-legged No. 3 stirrup along each side. The other two specimens were reinforced with two-legged No. 2 stirrups along each vertical side of the opening.

The results shown in Fig. 9 indicate that very large openings can be accommodated in the webs of joists without reducing strength, provided that stirrup reinforcement with a yield capacity nearly equal to the shear at the hole is provided at its vertical edges. Similarly, closely spaced multiple holes can be placed in a joist as long as each hole has side reinforcement. Specimens with multiple circular and oval holes failed in the struts as long as the width of the post, P, was greater than three-eighths the depth of the web.

For specimens with long rectangular holes, the addition of stirrups in the tensile strut was beneficial. Results of tests on these specimens are summarized in Table 1. It should be noted, however, that the addition of longitudinal bars adjacent to the tension side of the hole decreased strength. Apparently the addition of longitudinal bars adjacent to the tension side of the hole increases the stiffness of the tensile strut, thereby attracting a greater part of the total shear. Since the longitudinal bars do not provide increased shear capacity, the tensile strut fails prematurely in shear, thereby reducing the strength of the specimen.

From the analysis of data obtained on square openings [12], it was found that a point of axial compression occurred near the mid-length of the compressive strut at the opening. It was found that the magnitude of the axial compression force could be calculated from the external bending moment. Prior to first cracking, the distribution of shear between the regions above and below the opening was approximately in proportion to the cross-sectional area of the struts. After cracking, the compressive strut tended to carry all of the shear.

A conservative prediction of the strength of the specimens with square openings in unreinforced webs was obtained by calculating the load causing tensile cracking at the opening. A good prediction of the strength of the specimens with reinforced square openings that failed in the compressive strut was obtained from the lesser of the calculated loads causing either an eccentric shear compression or diagonal tension failure. In all cases, the strength provisions of the ACI Building Code were used as the basis for calculations.

4. Summary

To satisfy the basic requirement that any structure must have an adequate margin of strength to resist overload and must be serviceable under normally expected loads, structural concrete members containing openings should be evaluated on the basis of strength, deflection and cracking. When possible, analytical means should be used to evaluate members containing openings. However, in many cases, no suitable analytical evaluation of structural concrete members containing openings is available. Under these circumstances, physical tests can be used to determine strength and serviceability.

The experimental results which were summarized indicate that metal ducts can be placed in floor systems without significantly changing the structural performance. Tests also showed openings can be placed through webs of concrete joists.

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Table 1. Effect of Different Types of Reinforcement

Rectangular Opening (See Fig. 7)	Shear Reinforcement	$\frac{V_u}{b'd\ f'_{sp}}$
H = 4 in. W = 16 in. X = 32 in. Y = 8 in.	Side Reinforcement (No. 3 stirrups)	0.47
	Side Reinforcement plus No. 2 Stirrups in Tensile Strut[2]	0.53[1]
	Side Reinforcement plus No. 4 Longitudinal Side Bars in Tensile Strut	0.44
H = 4 in. W = 28 in. X = 32 in. Y = 8 in.	Side Reinforcement (No. 3 stirrups)	0.37
	Side Reinforcement plus No. 2 Stirrups in Tensile Strut	0.46
H = 4 in. W = 40 in. X = 32 in. Y = 8 in.	Side Reinforcement (No. 3 stirrups)	0.30
	Side Reinforcement plus No. 2 Stirrups in Tensile Strut[2]	0.37
	Side Reinforcement plus 2 No. 4 Longitudinal Side Bars in Tensile Strut	0.24

Notes:

[1] Specimen failed in flexure away from hole. All others failed in shear at hole.

[2] Stirrups hooked around 2 No. 2 longitudinal bars adjacent to tension side of hole.

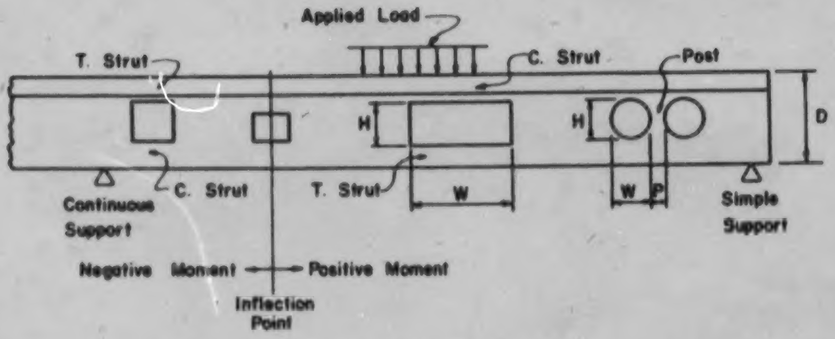

Applied Load
T. Strut
C. Strut
Post
H
H
D
C. Strut
T. Strut
W
W
P
Continuous Support
Simple Support
Negative Moment
Positive Moment
Inflection Point

Fig. 1 - Openings in Concrete Beams

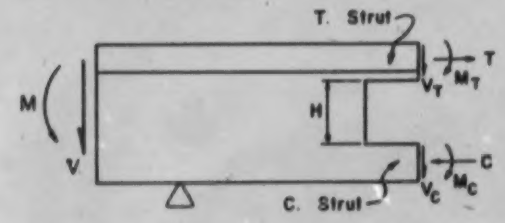

T. Strut
T
M_T
V_T
M
H
V
C
M_C
V_C
C. Strut

Fig. 2 - Forces Acting on Struts

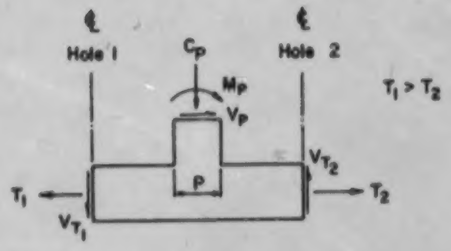

℄ Hole 1
C_P
℄ Hole 2
M_P
V_P
$T_1 > T_2$
V_{T_2}
T_1
P
T_2
V_{T_1}

Fig. 3 - Forces Acting on Post

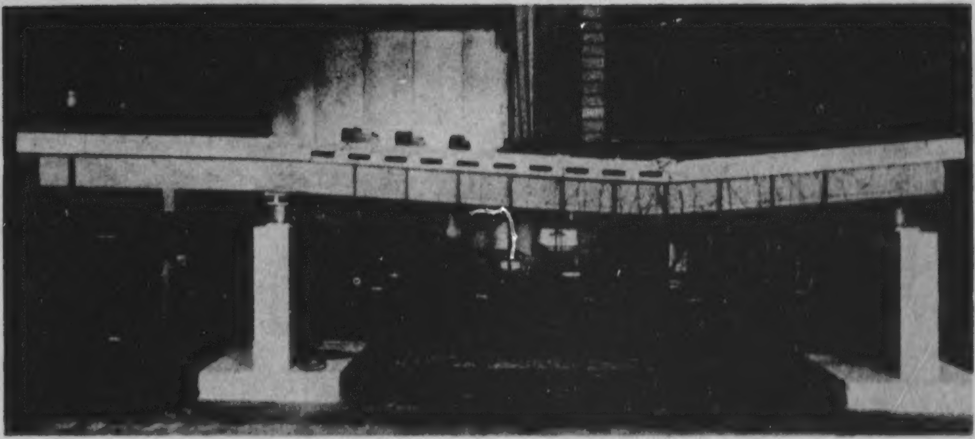
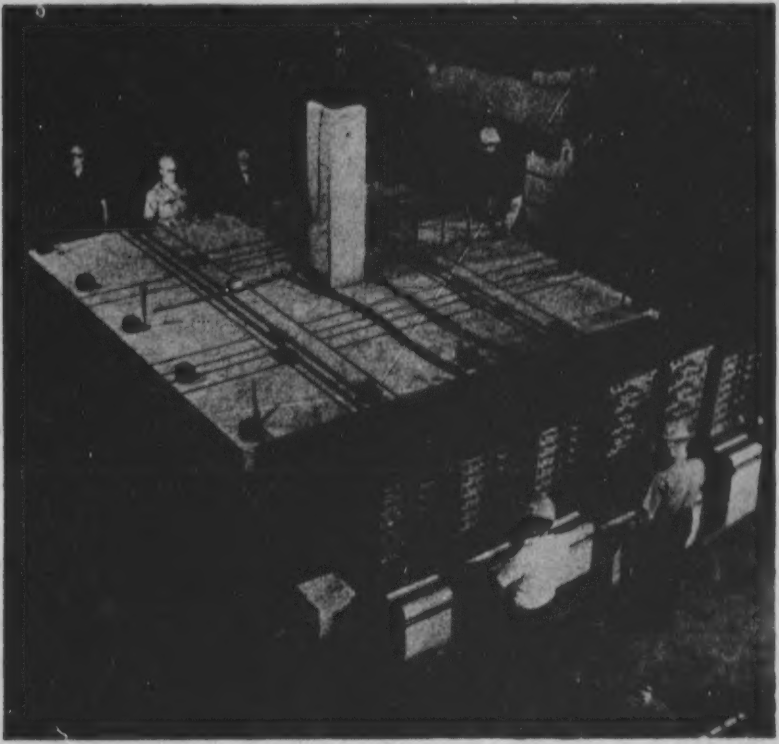


Fig. 4 - Specimen with Duct, After Testing to Destruction

Fig. 5 - Test of Slab-Column Specimens Containing Duct



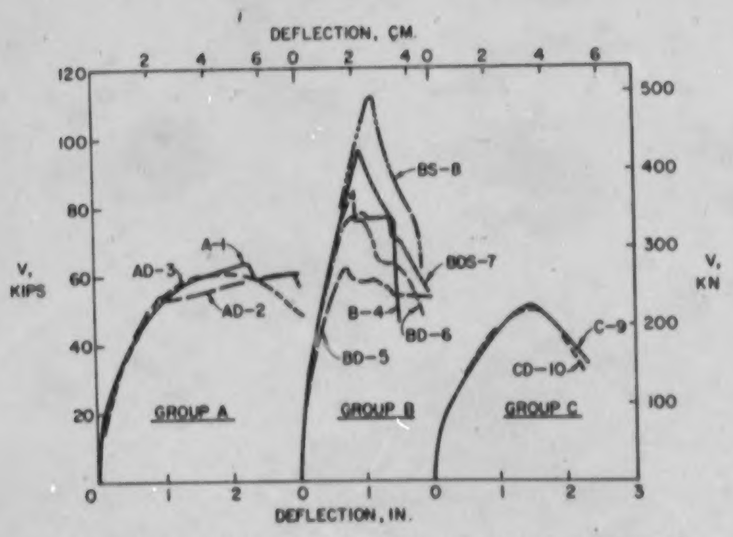


Fig. 6 - Edge Deflections of Slab-Column Test Specimens

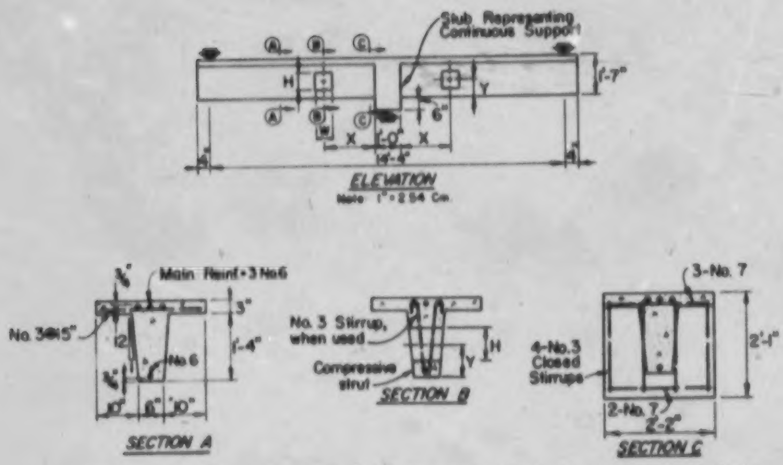
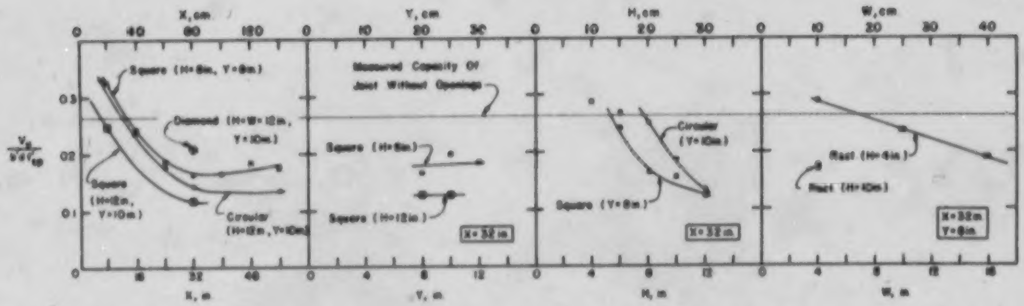
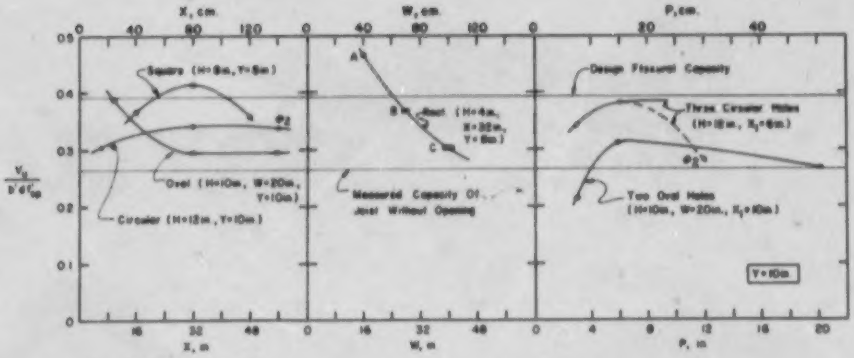

Stub Representing Continuous Support
A
B
C
H
Y
1'-7"
6"
X
1'-0"
X
14'-4"
4"
4"
ELEVATION
Note 1" = 2.54 Cm.
3/4"
Main Reinf = 3 No.6
3"
No. 3@15"
12
1'-4"
No.6
3/4"
10"
6"
10"
SECTION A
No. 3 Stirrup, when used
H
Y
Compressive strut
SECTION B
3-No. 7
4-No.3 Closed Stirrups
2'-1"
2-No. 7
2'-2"
SECTION C

Fig. 7 - PCA Test Specimen Representing Continuous Joist



Note All ordinates computed assuming b'=6in., the minimum width of the web

Fig. 8 - Effect of Unreinforced Openings



Note All ordinates computed assuming b'=6in., the minimum width of the web

Fig. 9 - Effect of Side Reinforcement

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

A Performance Approach to the Design of Fire-Resistive Buildings

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For many years, fire-endurance requirements for building structures and fire-insurance rate schedules for buildings have been based on performance demonstrated in standard fire tests. However, many conditions that may be encountered in an actual building, such as structural restraint, and partial or nonuniform fire exposure are in no way covered by standard fire test procedures. Therefore, the results of standard fire tests (as presently defined) may not represent the performance to be anticipated in a building. The structural performance of a building during a fire depends on the temperatures reached by the structural members of the building independent of how such temperatures are attained. Therefore, an analytical approach to the determination of fire resistance should be considered based on appropriate temperature limits for the structural materials of the building. Fire-resistive design may then be accomplished by providing adequate thermal protection to the structure so that the temperature limits of the structural materials will not be exceeded.

Depuis de nombreuses années, les règlements de tenue au feu pour les bâtiments et les barèmes d'assurance contre l'incendie sont fondés sur la performance indiquée par les essais normalisés de résistance au feu. Cependant, bien des conditions qui peuvent être rencontrées dans un bâtiment réel, telles que les limitations structurales et l'exposition partielle ou incomplàte au feu, ne sont pas couvertes par les procédés normalisés d'épreuve au feu. De ce fait, les résultats des essais normalisés au feu (tels qu'ils viennent d'être définis) peuvent ne pas représenter la performance qu'on est en droit d'attendre d'un bâtiment. La performance structurale d'un bâtiment pendant un incendie dépend des températures atteintes par les éléments de structure du bâtiment quelle que soit la façon dont ces températures ont été obtenues. Donc, une approche analytique pour la détermination de la résistance au feu devrait être considérée sur la base de limites de température appropriées pour les matériaux des structures du bâtiment. Une étude en vue de la résistance au feu pourrait alors être réalisée en fournissant une protection thermique au bâtiment de sorte que les limites de température des matériaux de structure ne soient pas

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dépassées. Au lieu d'essais en vraie grandeur des assemblages de constructions, des essais spéciaux à échelle réduite pourraient être requis pour établir les propriétés thermiques, l'adhésivité et l'intégrité structurale des matériaux de protection soumis à des températures d'incendie. Les résultats de tels essais pourraient alors être adaptés à des bâtiments réels par l'application d'une théorie appropriée des transferts de chaleur. Des exemples d'études en vue de la résistance au feu, pour des applications déterminées sont incluses dans la communication.

Key words: Building design; fire protection; fire resistance; fire-resistive buildings; structural design.

1. Introduction

When the need for fire-resistance standards was recognized in the latter part of the 19th century, a direct approach to the development of such standards was taken and a system of fire tests based on a standard fire exposure was established. In the United States this system of tests for structural members and building assemblies is described in ASTM Methods E-119, and similar test procedures have been introduced in other countries throughout the world.

Basically, these standards prescribe the conditions of fire exposure, the minimum size of the test specimen, and the conditions of structural loading for building components tested under load. However, many conditions that may be encountered in actual buildings, such as structural restraint, and partial or non-uniform fire exposure are in no way covered by standard fire test methods. Therefore, the results of these limited-size standard fire endurance tests cannot be considered representative of the performance to be anticipated during a fire in a building. Yet satisfactory structural performance in buildings during fire exposure must be assured if standards are to be relied upon for the protection of life and property. This paper presents a discussion of the effects of fire on building structures and suggests some improved methods for designing buildings to withstand these effects.

2. Structural Effects in Building Fires

The structural behavior of a building during fire exposure depends (in a complex manner) on the magnitude and distribution of elevated temperatures developed in the structural members of the building during the fire. If such elevated temperatures and the physical and thermal properties of the members are known, it is possible to compute the forces and movements which may occur and in this way the structural performance of the building during a fire can be estimated. Computer programs based on theories that can predict large deflections and can operate beyond the elastic limit of structural materials are available to analyze complete buildings. However, such programs are generally very complex and a large number of input variables may be involved to obtain results suitable for design purposes. Therefore, a complete analysis may be too costly except for very large building projects. For smaller buildings, simplified programs have been developed, but these limited programs often consider only parts of the building and they must be used with caution to insure that the assumed material properties and boundary conditions are representative of the building being studied. If all components of the building are not considered in the analysis, unreliable results may be obtained and the analysis, like an improperly conducted fire test, will be useless.

Because of the complexity and expense of a complete structural analysis, an approximation is frequently made relating structural performance directly to some limiting temperature. This approximation is based on the assumption that adequate structural integrity will be maintained in a building as long as the temperature of the structure does not exceed the value at which its strength is reduced below the allowable stress used for design. (This approximation is also used for evaluating performance in many standard fire tests conducted without structural load [1,2,3],[2] and a considerable amount of evidence has been presented to demonstrate its usefulness and validity [4]. For common building materials strength-temperature data is readily available, and therefore temperature limits are easily set if this approximation is used.

But, regardless of how temperature limits are established for the structure—whether by rigorous structural analysis or by acceptance of the design approximation discussed above—it will be convenient to divide the design of a fire-resistive building into two parts—one thermal and one structural—with temperature as the coordinating factor between them.

If a structural analysis is performed, it may be conducted without regard for actual fire exposure characteristics simply by assuming temperatures for various parts of the building and checking for satisfactory structural performance. Therefore, the maximum temperatures of the structure that can be permitted during fire exposure without causing unacceptable damage to a building can be established. If the design stress approximation is used, a temperature limit may be selected directly from published strength-temperature data for the materials used in the construction. For structural steel, limiting temperatures in the range 1000 to 1200 F (538 to 648 C) are commonly used. But high-strength prestressing strand is normally limited to 800 F (426 C) maximum temperature. It would seem appropriate to establish similar limits for other structural materials, but this has not been normal practice.

3. Thermal Effects in Building Fires

After temperature limits have been determined for the structure by one of the methods described above, thermal computations can be performed to determine the amount of insulation (fire-proofing) required to maintain structural temperatures below the established limits. But fires may be large or small, of high or moderate temperature, and of long or short duration, and therefore it is difficult to define the appropriate fire characteristic to be used as a basis for evaluating thermal effects in a particular building fire. The definition of fire exposure simply by specification of a time-temperature curve is not satisfactory. Radiation and convection heat transfer properties must also be specified. The suggestion by Harmathy and Lie [5] that the standard time-temperature curve be replaced by a heat flux-versus-time relationship should be considered seriously. Many other investigators have also made significant contributions to the study and interpretation of fire severity and an excellent review of their works has been presented by Robertson and Gross [6]. But further study of the fire severity may be necessary to obtain satisfactory correlation with actual building fires.

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[2] Figures in brackets indicate the literature references at end of this paper.

However, regardless of what fire exposure characteristics are assumed, thermal computations may be made to determine the temperatures developed in structural members during the fire using any fire-proofing materials for which physical and thermal properties are known. Or, if the properties are not known, heat transfer tests of selected portions of building constructions may be conducted to enable direct measurement of temperatures attained during fire exposure. Such tests could be simple because the size of the specimen would be determined by heat transfer considerations rather than by structural conditions. In addition to providing a means for measuring thermal performance, the tests should also provide methods to evaluate the reliability of fireproofing materials at high temperatures.

If the standard time-temperature curve is used to define fire exposure in these tests, the results may be expressed in hours of fire endurance and such results may be interpreted directly in terms of building code requirements which are usually specified in hourly fire resistance ratings. Nonstandard fire exposures may be more realistic, but performance based on nonstandard fires is not often readily accepted by building officials unless such fires are converted in some way to equivalent standard exposures.

Then, as sufficient information becomes available, the need for testing can be reduced and the amount of fireproofing required for a particular application may be determined by calculation.

4. Practical Considerations

Although it is conceivable that a completely analytical approach to the design of fire-resistive buildings may be accomplished by use of complex computer programs involving both structural and thermal effects, such an approach is not suitable at this time for acceptance under many building codes because most codes (and the standards on which they are based) are oriented toward the fire resistance of individual building components instead of toward the performance of complete structures under realistic fire exposure conditions. Therefore, it appears necessary to continue, at least for some time, to design fire-resistive buildings on the basis of the performance of building components under conditions of some standard fire exposure. Test procedures may be simplified or replaced by thermal and structural computations as confidence is developed in new analytical techniques. But until building codes are revised to specify fire resistance on some basis other than by reference to specific building elements subjected to a standard fire exposure, it will be necessary to express performance in hours of standard fire exposure.

Another obstacle to the use of completely analytical methods for the design of fire resistive buildings is the result of a requirement often found in building codes, that various building elements have different fire resistance ratings. For example, the columns of a high-rise building may be required to have a 4-hour fire resistance rating but beams may be required to have only a 3-hour rating. Such multiple rating requirements would add complication to calculations for the complete building but not to calculations involving individual building components.

But coordination with the requirements of building codes is not the greatest difficulty in gaining acceptance of a performance approach to the design of fire-resistive buildings based on analytical methods. Perhaps the greatest obstacle at this time is the lack of useful design information about the performance of fire-resistant materials at high temperature. Many materials, such as gypsum, provide excellent fire protection if they remain in place during fire exposure. However, such materials lose strength rapidly at high temperatures after their moisture is driven off and they may shrink and crack and fall from the surface they are intended to protect [7]. This is particularly true with membrane-type protection systems where the insulating material is applied in board form to provide a ceiling or wall surface which also acts as a fire-resistive barrier. For direct-contact fireproofing materials such as sprayed fiber or cementitious mixtures, there is also a need for reliable information about adhesion and durability at high temperatures. In many cases, the expansion of structural members that may occur during fire exposure can cause cracking and separation of the fireproofing from the protected surface if the adhesion properties are not adequate. Standard fire test methods in common use today may not provide a reliable measure of the durability of materials during actual fire exposure because standard test conditions are so unlike those which may occur during actual building fires. Methods of measuring the durability of fireproofing materials under conditions typical of actual fire exposure are urgently needed and design procedures should be developed so that reliable performance can be assured when such materials are used to protect building structures from fire.

5. A Recommended Design Procedure for Fire-Resistive Buildings

Based on information presented in this paper, the following procedure is recommended for the design of fire-resistive building structures. It is recognized that the method is not ideal. But in view of the practical considerations referred to above, it is believed to be considerably better than the standard procedures normally used today.

1. Establish design temperature limits for all materials used in the building structure. These temperatures should be based on material properties as a function of temperature and on the allowable stresses used for design of the structure. Or, when a thorough and reliable structural analysis indicates other temperature limits are more suitable, those should be used if acceptable under the building code.

2. For fire exposure conditions expected to occur in the building, determine the thickness of fireproofing required to maintain temperatures below the limits established in Step 1. This determination may be made by computation if reliable information about

> the durability and elevated-temperature properties of the fireproofing material is available, or if adequate material data is not available, the fireproofing performance may be established by carefully planned tests of representative parts of the structure. If compliance with the building code requires a rating based on the standard time-temperature curve, the standard fire exposure conditions should be used in making the computations or conducting the tests.

A definite advantage of the proposed method is its compatibility with existing codes and test procedures. The only significant changes from ASTM Methods E-119 would be the elimination of the structural loading requirement in testing of floors and load-bearing walls and the introduction of temperature limits for all structural materials. The standard time-temperature curve could still be used to define fire exposure until more information is obtained about fire severity and the performance of fire-resistive materials at high temperature. But as this information becomes available, the standard time-temperature curve should be replaced by more realistic fire exposures for both tests and calculations.

Support for the concept of using temperature as a criterion of structural performance during fire exposure has been demonstrated recently by changes in ASTM Methods E-119 and UL263. Because it has been recognized that the structural loading arrangement and the size of the test assembly used in fire tests may not be representative of conditions in an actual building, lack of confidence has developed in the acceptance of the results of such tests of some building assemblies. Therefore, ASTM and Underwriters' Laboratories have introduced temperature limits as additional end-point criteria for structural steel in floors and beams tested according to their standards. However, the structural load requirement was not eliminated from the test procedure when these limits were introduced and no temperature limits were established for materials other than steel. This is not a logical adjustment to the standard because the disparity between loading in the test specimen and the building exists for all materials used in the construction—not just for the steel. Therefore, temperature limits based on analytical studies or design stress limits should be imposed on all materials so that reliable performance during fire exposure in actual buildings may be expected.

6. Examples of Fire Resistive Designs Based on Performance

Two recently developed methods of providing fire protection for exposed structural steel have been based on the design procedure given above. One of these methods involves the principle of flame shielding and the other involves the use of liquid-filled columns. Both methods have been reported in detail elsewhere [8,9,10,11] and therefore only a brief summary will be given here.

Flame shields have been approved for use on buildings in New York and Chicago, based on demonstration of performance by both calculations and tests. Liquid-filled column systems are now (1971) in use in six buildings in the United States and at least two in Europe. In the United States, performance has been demonstrated by calculations based on well-established heat transfer data and no fire tests were required to gain acceptance. But in Europe both calculations and tests have been conducted in support of liquid-filled column systems.

An important advantage of these fire protection methods which permit the use of exposed steel in building construction is that they do not depend on insulating coatings to achieve the required protection. Therefore, one of the most troublesome design variables—the performance of fireproofing materials at high temperature—does not need to be considered.

The principle of flame shielding and the heat transfer equations which apply to an exposed spandrel girder are shown in Figure 1. Essentially, the shield (which is also the insulated bottom flange of the girder in this example), prevents direct impingement of flame on the web of the girder and therefore the exterior surfaces of the girder receive heat from the flame by radiation only. But these surfaces may also dissipate heat to cooler surroundings by both convection and radiation and for many building applications, excessively high steel temperatures will not be reached and the strength of the girder will not be seriously affected.

Design calculations reported in Reference 3 for a 54-story office building in New York City predicted that a maximum spandrel temperature of 680 F (360 C) might be expected during an actual fire in the building and a burnout test which was conducted to support the design indicated a measured value of 640 F (337 C).

Other tests conducted for 3 hours, during which the temperature was controlled according to the standard time-temperature curve, also indicated maximum spandrel web temperatures of about 600 F (316 C). These temperatures are well below the range of 1000 to 1200 F (538 to 648 C) normally considered as a limit for structural steel, and therefore the use of flame shields was considered to be an effective method of fire protection for the spandrel girders of this building. Other buildings may also be designed with flame-shielded exterior members, but specific calculations should be made for each particular application.

Liquid-filled columns are another example of the design of fire-resistant structural members based on performance. Both calculations and test results have indicated that excessive steel temperatures will not be reached by liquid-filled columns in building fires as long as the columns are maintained full of liquid. Therefore, if an adequate supply of liquid is available, a reliable liquid-filled column fire protection system may be developed.

A schematic arrangement of one design of liquid-filled column system is shown in Figure 2. This type of system has been used in the 64-story U. S. Steel Building in Pittsburgh and in the BFI Building in Dusseldorf. Storage tanks in the U. S. Steel Building contain a reserve capacity of 2000 gallons (7.5 m^3) to provide a 4-hour fire resistance based on the standard fire exposure and a maximum temperature of 640 F (337 C) has been calculated for the 4-inch-thick column plates at the base of the building. The standard time-temperature curve was used in making these calculations for tank size and steel temperature. In the BFI Building, the storage tanks have a capacity of 1180 gallons (4.5 m^3) and actual measurements taken during a fire test in the building indicated an average maximum steel temperature of 401 F (205 C) which is in good agreement with 446 F (230 C) predicted by calculation [12].

7. Conclusions

These examples of fire resistive designs have been given to illustrate an analytical approach to structural fire protection in buildings. Although the cases given represent special applications of bare exterior steel, the same design principles may be applied to more conventional construction if suitable temperature limits can be established based on a structural analysis and confirmed by special tests. The special structural tests might be conducted using scale models which could be much more representative of actual building construction than is now possible within the limitations of the standard furnace test methods. Heating of selected portions of the models could be accomplished by any convenient means (such as by use of electrical elements attached to individual structural members) since the purpose of the tests would be to measure structural performance and not fire resistance in terms of time. Limiting temperatures for conventional structural systems based on such analyses and tests could then be tabulated for use by designers and building officials. In this way simple specifications of maximum temperatures to be permitted in structural elements during fire exposure could be set up without the need for repetitive testing or complex analyses for each building design. If suitable temperature limits during fire exposure can be established, fire-resistance ratings may be developed for any fire-resistive material or system by heat transfer analyses supported by suitable tests to confirm the thermal and physical performance of the protective materials under fire exposure conditions. These fire tests would not need to be tests of complete building constructions as is the case under present standards. Instead, the tests could be designed to measure the thermal performance and the durability of protective materials applied to limited portions of representative building components. Much effort will be required to develop suitable test procedures which can provide the basis of reliable fire-resistance design, but it is suggested that such effort will be rewarded by improved and more reliable design of fire-resistive buildings.

It is important to recognize that the design procedures recommended in this paper will not eliminate the need for testing in connection with fire research. Standard test procedures may need to be changed or discarded. But new standards will need to be developed and fire testing will become more meaningful and more important.

As research provides more information about fire severity and the performance of materials exposed to fire, it is hoped that further progress can be made toward a performance approach to the design of fire-resistive buildings.

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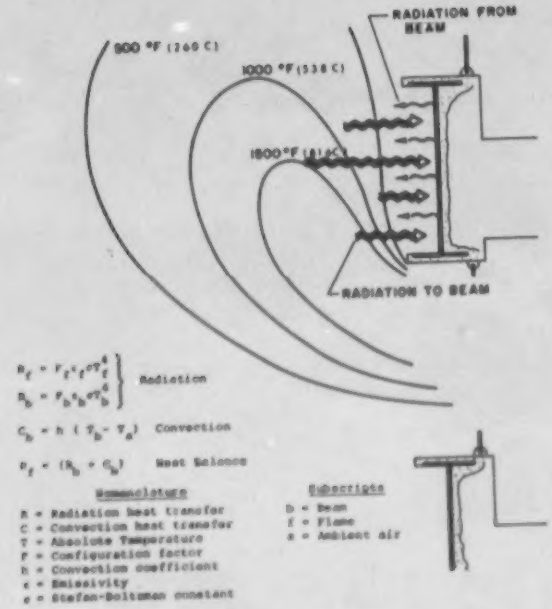
RADIATION FROM BEAM
500 °F (260 C)
1000 °F (538 C)
1500 °F (816 C)
RADIATION TO BEAM

$$\left.\begin{array}{l} R_f = F_f \epsilon_f \sigma T_f^4 \\ R_b = F_b \epsilon_b \sigma T_b^4 \end{array}\right\} \text{Radiation}$$

$$C_b = h\,(T_b - T_a) \quad \text{Convection}$$

$$R_f = (R_b + C_b) \quad \text{Heat Balance}$$

Nomenclature

R = Radiation heat transfer
C = Convection heat transfer
T = Absolute Temperature
F = Configuration factor
h = Convection coefficient
ε = Emissivity
σ = Stefan-Boltzman constant

Subscripts

b = Beam
f = Flame
a = Ambient air

FIGURE 1
Flame Shielding
for Exterior Surface of Spandrel Girder

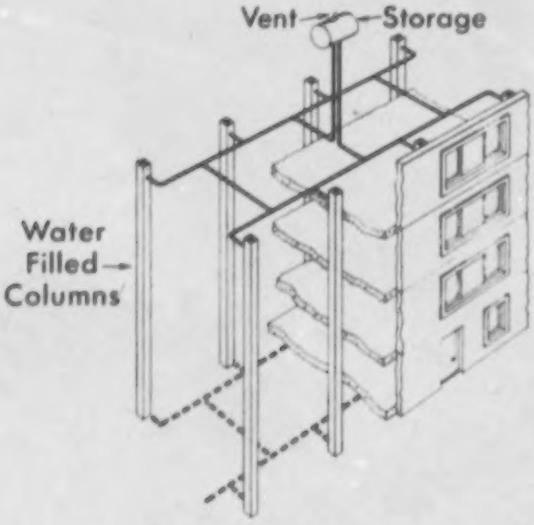
Vent
Storage
Water
Filled
Columns

FIGURE 2
Schematic Arrangement
of Liquid-Filled Column Fire Protection System

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

The Resistance of Brick Walls to Lateral Loading

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The Building (Fifth Amendment) Regulations 1970 lay down performance requirements to prevent progressive collapse, following an incident, in buildings of 5 storeys or more. Essentially either the building must be so designed as to provide alternative paths of support in the event of the removal of a main structural member, or the members must be designed to withstand a lateral load of 5 lbf/in^2. Laboratory tests to determine the lateral strength of various types of brick wall are briefly described and the application of the results to the evaluation of the performance of real buildings discussed. It is concluded that solid brick walls more than 7 in. thick may be "deemed to satisfy" the requirements of the Fifth Amendment.

Les Règlements de la Construction de 1970 (5ème amendement) formulent les exigences de performance pour prévenir l'affaissement progressif, à la suite d'un incident, de bâtiments de 5 étages ou plus. Esentiellement, ou bien le bâtiment doit être conçu de telle sorte que des appuis de relais soient prévus en cas de déplacement d'un élément de structure majeur, ou bien les éléments doivent être conçus de façon à résister à une charge latérale de 5 livres par pouce carré. Des essais de laboratoire pour déterminer la résistance latérale de divers types de murs de briques sont brièvement décrits et l'application des résultats à l'évaluation de la performance de bâtiments réels est examinée. On en conclut que des murs de briques solides épais de plus de 7 pouces sont considérés comme satisfaisant les prescriptions du 5ème amendement.

Key words: Brickwork; experimental; lateral loading; performance; research; residential structures; safety; structural masonry.

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1. Introduction

The Ronan Point Disaster in May 1968 focussed attention on the hazards of gas explosions in domestic structures. This happened in a 22 storey precast concrete panel construction and the removal by the explosion of an external load-bearing flank panel led to collapse of the storeys above. In falling the debris caused progressive collapse of the floor and wall panels in the corner of the block right down to the podium.

The Tribunal considered [1][2] that the cause of the explosion was town gas and that the pressure built up in a few milliseconds to a peak of some 5 or 6 lbf/in^2 (34 or 41 kN/m^2) and then fell away so that for about 1/10th of a second the flank wall was subjected to an average pressure of about 3 lbf/in^2 (21 kN/m^2). The maximum pressure was considered to be 12 lbf/in^2 (82.74 kN/m^2) in the hall. Subsequent experiments by B.C.R.A. [2] have shown that both the pressures and times to reach these pressures are unusual for gas explosions but it must be remembered that these experiments have the benefit of direct measurement while the Tribunal had only post hoc statements and simulation tests to assist it.

The Tribunal was clearly of the opinion that the risk was confined to system-built structures and said "For low system-built blocks - say six storeys and under - it seemed to us that the risk was in much the same category as that in the very many traditional buildings with load-bearing brick walls. But with taller system-built blocks - and in this country there are already some 30,000 flats in such blocks - the risk enters new dimensions . . ."

As a result of the recommendations of the Tribunal the Government issued a circular 62/68 [3] in November 1968 which laid down certain standards for new buildings in large panel construction.

"There are two basic methods of avoiding progressive collapse, namely:

Method A By providing alternative paths of support to carry the load, assuming the removal of a critical section of the load-bearing walls.

Method B By providing a form of construction of such stiffness and continuity so as to ensure the stability of the building against forces liable to damage the load-supporting members.

For these purposes, the forces should be assumed as being equivalent to a standard static pressure of 5 lbf/in^2 (34.47 kN/m^2). This standard should be used in designing new buildings. Where residual risks are lessened by the control of the incidence of an explosion in magnitude or frequency, a corresponding reduction may be made in the pressure."

The Institution of Structural Engineers issued, in December 1968, certain general recommendations on design against progressive collapse [4] which for the first time extended the scope of the regulations to load-bearing brickwork construction and other tall buildings with no frame. While other documents [5] [6] sought to clarify the confusion at this time, the important performance requirement first enunciated in Circular 62/68 was made mandatory in the Building (Fifth Amendment) Regulations 1970 [7] which came into force on the 1st April of that year.

The regulation is brief but covers all types of structure. There is no reference to explosions, but rather to an "incident" which applies only to one element of structure at any one time. While the preferred method may be to so design the structure that walls and floors bridge over the gap left by the removal of a structural element, the alternative is allowed of providing elements capable of resisting a pressure of 5 lbf/in^2 (34 kN/m^2). Thus a crucial performance requirement for walls is a resistance to lateral loading of this magnitude, and it was important to determine at which minimum values of vertical precompression various configurations of brickwork will withstand it.

It is perhaps appropriate to ask first how this performance requirement of 5 lbf/in^2 (34 kN/m^2) was arrived at. There are published data on the effect of blast on the outside of buildings. The most important of these publications [8] relates to very extensive experiments carried out in America on the effects of nuclear weapons. Various test structures were exposed to blast and the pressures measured. Thus a two-storey house with exterior walls of brick veneer with cinder block back-up withstood an overpressure of 1.7 lbf/in^2 (11.73 kN/m^2) with extensive damage to windows and internal partitions but was completely destroyed at an incident overpressure of 5 lbf/in^2 (34.47 kN/m^2). The exterior walls were exploded outwards, the roof demolished and blown off, and the brick chimney broken in several sections. The British Civil Defence authorities adopted the same pressure for the total destruction of houses.

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[2] Figures in brackets indicate the literature references at end of this paper.

While no explanation for the choice of this pressure in the Building (Fifth Amendment) Regulations has been forthcoming, the Structural Clay Products Research Foundation of America with more candour chose this as a design criterion because it is the upper limit of the probable effects of tornadoes, earthquakes and similar natural disasters and " . . . such a level of protection is probably the maximum economic level that the average owner can afford to build." [9]

2. Experimental

The present investigation was based on 4 ft. 6 in. long walls, storey-height, 8 ft. 4 in. 34 courses. The four kinds of brick used to build the more than 100 walls tested included solid, perforated and pressed frogged types with the mean compressive strengths varying from 4100-12450 lbf/in^2, water absorption (5 hour boil) of 4.8 - 23.3% and suction rates from 1.5 - 22.4 $g/dm^2/min$. Three mortars were used, 1.3 ciment fondu:sand, 1:¼:3 and 1:1:6 cement: lime:sand. The fondu walls were tested after 2-3 days and the remainder after 28 days.

The walls were tested to destruction in the B. Ceram. R.A. 1000 ton wall testing machine [10] modified to apply low vertical precompression loads and with the lateral load applied by a textile-reinforced rubber bag placed alongside the face of the test wall. One side of the bag is completely in contact with the whole elevation of the wall and the reaction is taken on the inside of the columns of the machine frame (fig. 1). The lateral pressure is applied by admitting compressed air to the bag so that an arbitrary rate of application of lateral pressure of ¼ $lbf/in^2/min$. is maintained.

The horizontal deflection is measured at the mid-depth of the wall. During the tests, due to this deflection of the wall, the effective height tends to increase. This increases the pressure of oil in the hydraulic ram, and the compressive load applied to the test wall is maintained constant by bleeding oil from the ram; this leads to an upward movement of the spreader beam. In practice, this increase in height of the wall would jack-up the floor slab and thus effectively increase the compressive load beyond the design value. Measurements of the upward movement of the spreader beam were made using transducers and a digital voltmeter. The exact magnitude of this movement is indeterminate since in the last moments before ultimate failure the wall enters a state of unstable equilibrium and there is rapid acceleration both in the buckling and vertical extension. However, the maximum extension before the wall leaves the state of stable equilibrium appears to be about 1/3 in.

At low precompressions failure is flexural until the tensile strength is exceeded after which it is entirely geometrical and the strength of the bricks and mortar play little part in the resistance to lateral loading. A crack forms at or about the mid-depth and the failure mechanism is hinge-like, the wall failing into two roughly equal halves. At intermediate values of precompression there is slight crushing failure of the face of the bricks in the region of maximum compression. At higher values of precompression, local crushing failure of the bricks and mortar occurs and there is multiple catastrophic failure of the wall. Here the strength of the wall will have a minor effect upon the lateral strength of the wall and this is brought out in the results of walls built from higher strength bricks. At very high values of precompression it is expected that the lateral strength will pass through a maximum value and would diminish to zero at the point where the compressive load reaches the ultimate strength of the wall, and this has been shown by Grenley et alia. [11] [12] .

The relationship between lateral load at failure and the precompression over the usual practical range is shown for the three most common thicknesses of solid walls in figure 2 together with 10½ in. cavity walls.

At these levels of precompression the behaviour of the wall approximates to that of a three-pinned arch.

An analysis of this behaviour is possible on the following assumptions:-

1. Rigid materials (including supports)-
2. Failure occurs by horizontal cracking at the top, centre and bottom of the wall, causing rotation about points A, B and C (fig. 3).

The forces on the wall are a vertical precompressive load and a uniform lateral pressure. Consider the forces acting on the top half of the wall and take moments about A (fig. 3).

$$f_c t l (t - d) = \frac{phl}{2} \cdot \frac{h}{4}$$

$$p = \frac{8 f_c t (t - d)}{h^2} \qquad (1)$$

where p is the applied uniform lateral pressure
f_c is the vertical compressive stress
l is the length of the wall
t is the thickness of the wall
h is the height of the wall
d is horizontal distance moved through by centre of wall.

If the precompressive load is constant throughout uplift of the wall at failure, then the maximum lateral pressure occurs when d = o

$$p = \frac{8 f_c t^2}{h^2} \qquad (2)$$

This reduces to the form

$$p = m\, f_c$$

$$\text{where } m = \frac{8t^2}{h^2} \qquad (3)$$

Values of m for the thicknesses and height of wall tested are 4½ in. = 0.0128; 7 in. = 0.0369; 8½ in. = 0.0561. Throughout this paper the actual thickness of walls has been quoted rather than the nominal thickness or co-ordinating size. The broken lines in figure 2 are derived from the three-pinned arch theory and it will be seen that they fairly represent the behaviour of walls under low values of precompression. In this zone the effects of brick compressive strength and mortar strength are negligible.

It can be seen in figure 2 that the lateral strength of two 4½ in. leaves tied with galvanised twisted steel ties to form a 10½ in. cavity wall is less than twice that of a single leaf of the same brick and mortar. The British Standard Code of Practice C.P.111 [13] stipulates in Clause 307 that the effective width of a cavity wall shall be taken as equal to two thirds of the sum of the widths of the two leaves. This gives m = 0.0228 and the broken line is based on this effective width.

The calculated lines all pass through the origin whereas regression lines calculated from the experimental data show a small intercept. The three-pinned arch theory ignores the restoring moment (see fig. 3) due to the self-weight of the wall; correction for this would result in a very small intercept on the lateral restraint axis. The arch theory also ignores the tensile strength of the wall, and since all the walls cracked long before ultimate failure, it follows that the flexural moment due to the tensile strength is less than the restoring moment due to the self-weight of the walls. The tests reported by Grenley et alia [11] [12] were carried out on walls built of high tensile strength mortars, in which case, in contrast to the present tests, the tensile strength of the brickwork would influence the resistance to lateral loading.

A number of walls 6 ft. 10 in. long with one or two returns have been tested. Comparing all these walls at a precompression of 5000 lbf/ft run, (73 kN/m) the lateral load resistance of various wall configurations is given in Table 1 and Table 2 shows the surprising homogenity of the results when expressed as a percentage increase over the no-return condition.

The importance of returns is thus established, but it should be noted that in practical terms these were very short walls. The failure of all walls with two returns is in a yield line pattern, so that the simple three-pinned arch method of calculation is not appropriate in this case.

3. Evaluation of the Performance of Buildings

In the Building (Fifth Amendment) Regulations, the loads to be used in designing a structural member which is essential to the structural stability of the building are:-

(a) the dead load
(b) one third of the live loads
(c) one third of the normal wind load
(d) 5 lbf/in^2 (34 kN/m^2) in any direction

Under these loading conditions a factor of safety of 1.05 is all that is required. In simple crosswall structures the load per foot run is mostly dependent on the type of floor used and the span. A typical range of loadings at mid-height is given in Table 3 for different numbers of storeys from the top (fig. 4) for internal walls when in situ concrete slabs are used. The figures include an allowance for finishes plus one third of the imposed load [14]

From figure 2 a minimum pre-load of 7200 lbf/ft for 8½ in. walls and 9700 lbf/ft run for 7 in. walls is required to achieve a lateral load resistance of 5 lbf/in^2 (34 kN/m^2). These pre-loads correspond to floor spans of about 15 ft. and 19 ft. respectively for 8½ in. and 7 in. walls at a level immediately below the top two storeys. At any lower level the Fifth Amendment is readily complied with.

The Regulation requires that structural failure following an incident be limited to the storey of the incident, the storey above and the storey below, so it is this third storey from the top which is crucial. In addition to the loads given in Table 3 the mode of failure requires that the building above the walls be lifted more than one third of an inch. Haseltine [14] has shown that considerable additional pre-load must be attracted to the wall due to the stiffness of the reinforced concrete floor slabs above. For a 12 ft. span and ¼ in. upward movement the pre-load would be increased by about one third. Since the presence of returns has been shown to increase the stiffness of walls, in most cases in practice the walls will resist even higher lateral loads.

Knowing the lateral strength of various wall types it is now a comparatively simple matter to design load-bearing brick buildings to meet the performance requirement either by providing alternative paths of structural support, or by ensuring that critical walls have a lateral strength in excess of 5 lbf/in^2 (34 kN/m^2).

4. Conclusions

A performance requirement has been set up in Great Britain for buildings of 5 storeys and more by the Building (Fifth Amendment) Regulations 1970. Tests on the lateral load resistance of walls have shown that three-pinned arch theory may be used to predict performance. In fact since the top two storeys are exempt, solid brickwork more than 7 in. thick may be "deemed to satisfy" the requirement of a lateral load resistance of more than 5 $\mathrm{lbf/in^2}$ (34 $\mathrm{kN/m^2}$) and minor changes in design enable load-bearing brickwork structures to be economically erected to provide buildings safe from progressive collapse.

5. Acknowledgements

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Table 1. Failure loads of walls with and without returns at a precompression of 5000 lbf/ft run (73 kN/m)

	No returns (Mean of 2)		One return		Two returns	
	lbf/in^2	kN/m^2	lbf/in^2	kN/m^2	lbf/in^2	kN/m^2
4½ in.	1.7	11.72	3.1	21.37	3.7	25.51
7 in.	3.2	22.06	5.5	37.92		
8½ in.	4.1	28.27	7.1	48.95	9.1	62.74

Table 2. Increase in failure load as proportion of no return condition

	No returns	One return	Two returns
4½ in.	1.0	1.82	2.18
7 in.	1.0	1.72	-
8½ in.	1.0	1.73	2.24

Table 3. (After Haseltine) Static load per ft. run on internal walls at mid-height of storey

Span		Slab depth		Load lbf/ft run		
				2 storeys down (At A)	3 storeys down (At B)	4 storeys down (At C)
ft	m	in	mm			
10	3.05	5	125	5100 (80 kN/m)	6900 (107 kN/m)	8700 (135 kN/m)
12	3.66	5	125	6200 (97 kN/m)	8400 (131 kN/m)	10600 (165 kN/m)
15	4.57	6½	163	7600 (118 kN/m)	10200 (159 kN/m)	12900 (200 kN/m)
18	5.49	7	175	9200 (143 kN/m)	12300 (192 kN/m)	15500 (241 kN/m)
24	7.32	9	225	13400 (209 kN/m)	18000 (281 kN/m)	22600 (352 kN/m)

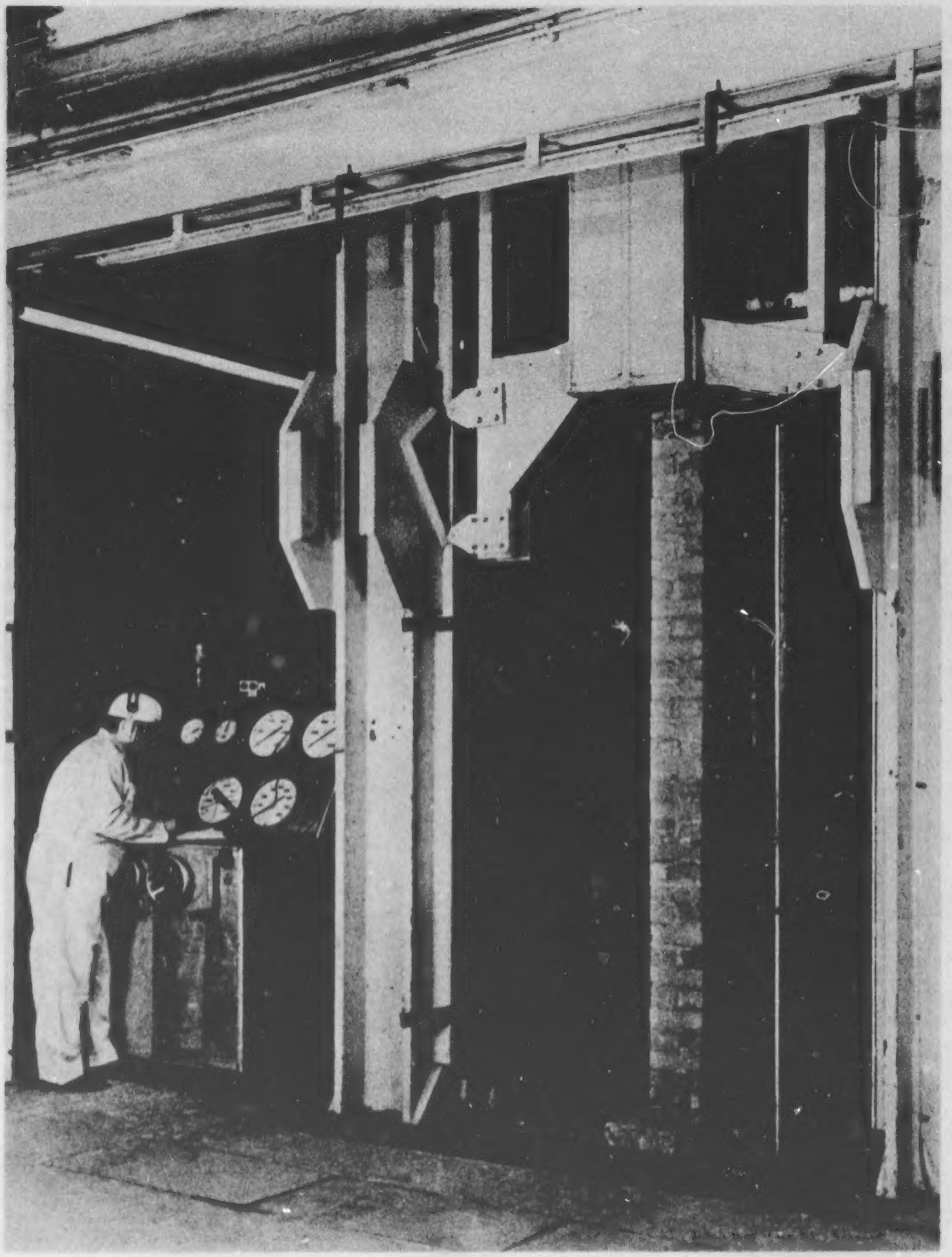
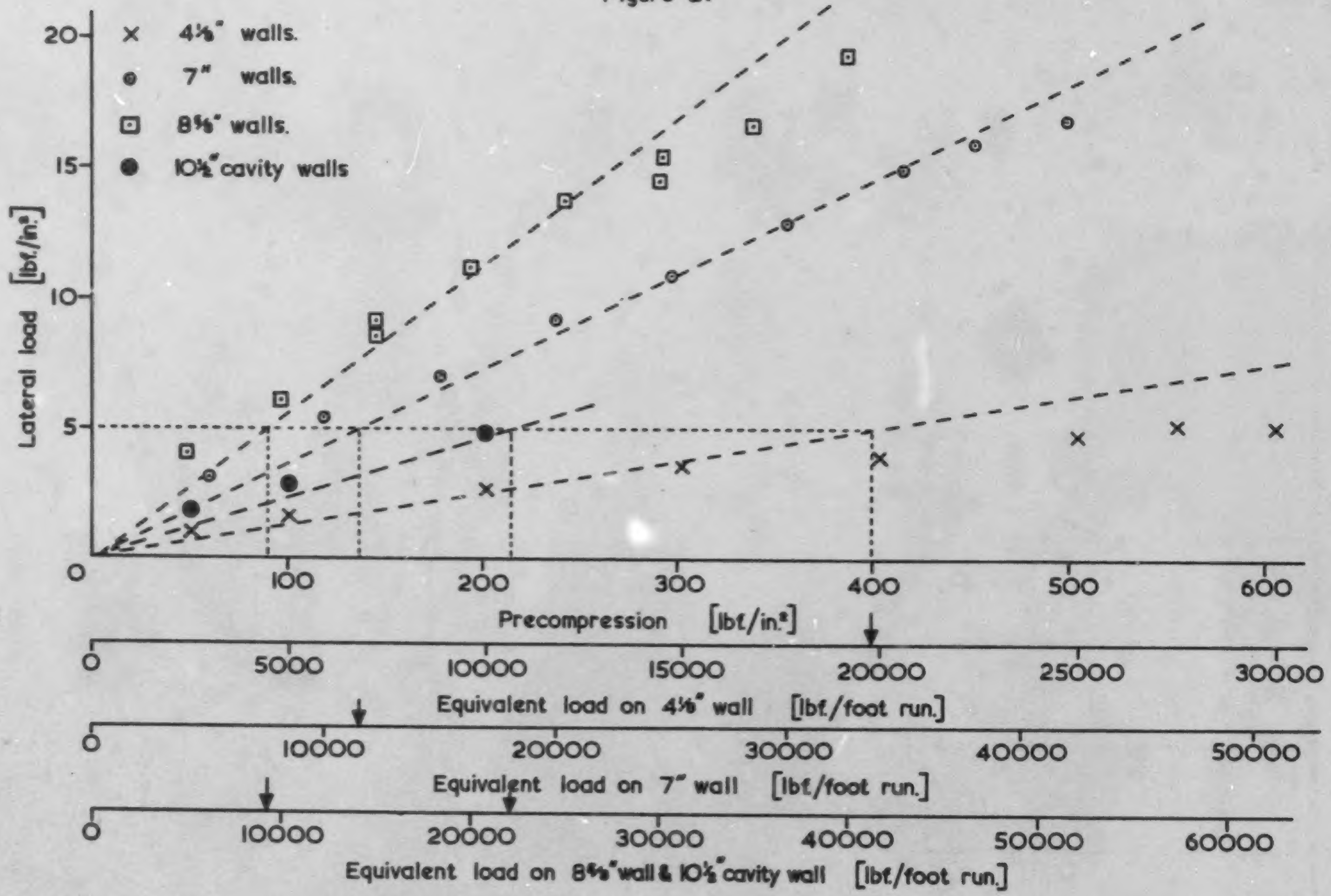
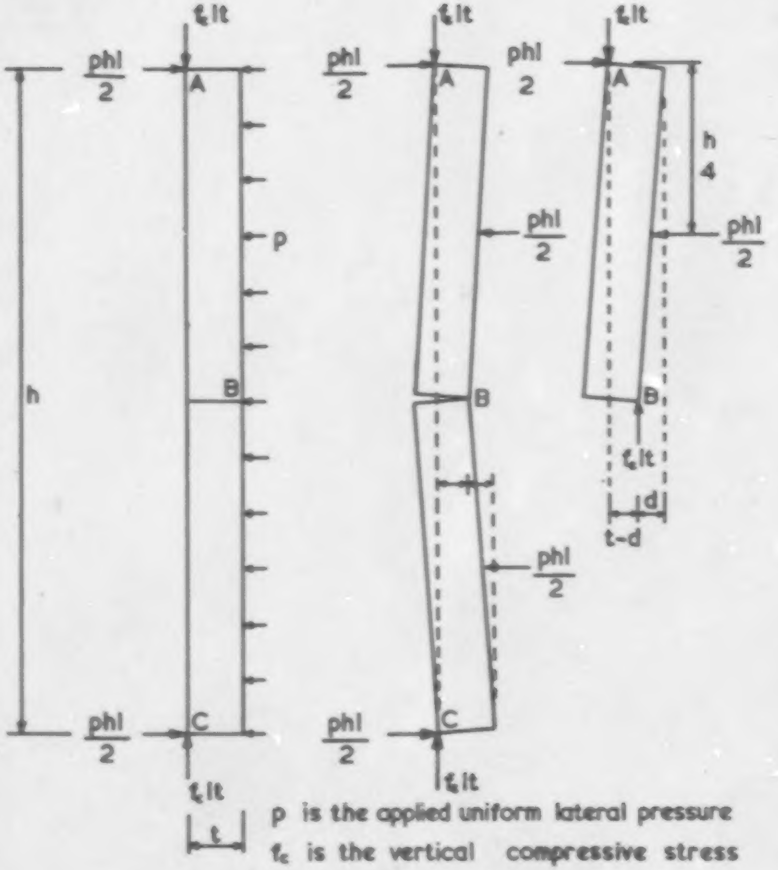


Fig. 1 Arrangement of wall testing frame for applying lateral load.

Figure 2.



Relationship between lateral load at failure and precompression 4½, 7, 8½ in. solid walls and 10½ in. cavity walls


$f_c lt$
$\frac{phl}{2}$
A
B
C
p
h
t
$\frac{h}{4}$
d
t-d

p is the applied uniform lateral pressure
f_c is the vertical compressive stress
l is the length of the wall
t is the thickness of the wall
h is the height of the wall
d is the horizontal distance moved through by centre of wall

Fig. 3 Three-pinned arch theory mechanism of failure

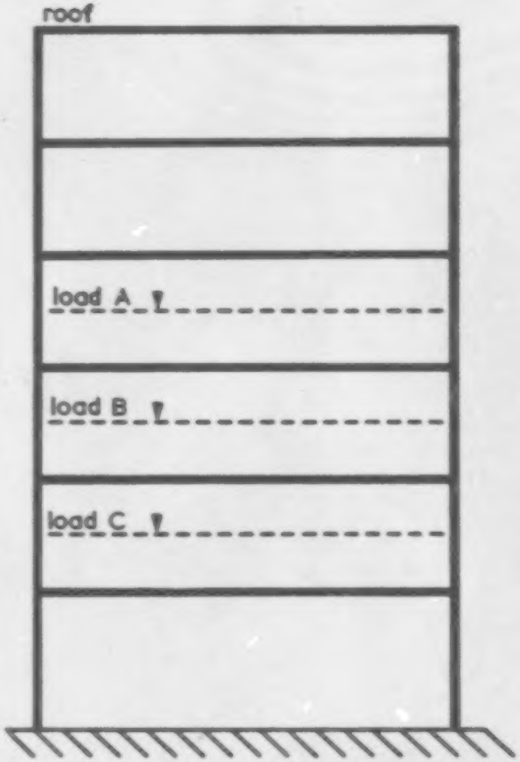

roof
load A
load B
load C

Fig. 4 Position of application of loads given in Table 2 (After Haseltine)

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

Experimental Gas Explosions in Load-Bearing Brick Structures

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The resistance of normal types of fenestration and cladding, masonry walls, and a full-size load-bearing brickwork structure to explosions of town gas/air and natural gas/air mixtures was determined. The explosions were generated by igniting stoicheiometric gas-air mixtures in balloons, or layered mixtures in the explosion space. Peak pressures were recorded by transducers. Explosion damage to the structure is discussed. Normal windows and cladding failed at pressures below 1 lbf/in^2 and in so doing provided venting relief limiting the maximum pressure developed, in accord with a simple formula. Under a precompression of about 30 lbf/in^2 a cavity wall will crack at about 3.3 lbf/in^2. A 4½ in. wall fully restrained by returns failed at about 5 lbf/in^2 and a 9 in. wall fully restrained cracked but did not fail at 15 lbf/in^2. In a normally vented simulation of a full-scale real domestic situation, it was not possible to raise an explosion pressure greater than just over 3 lbf/in^2. Possible amplification of explosion effects due to cascade or turbulence in interconnected rooms is briefly discussed and will be studied further.

La résistance de types normaux de fenêtrage et de revêtement, de murs de maçonnerie et d'une structure porteuse en briques en vraie grandeur aux explosions de mélanges de gaz d'éclairage/air et gaz naturel/air a été déterminée. Les explosions étaient provoquées par l'ignition de mélanges stoichiométriques de gaz/air en ballons ou de mélanges par couches dans l'espace d'explosion. Les pressions maximales ont été enregistrées au moyen de transducteurs. Les dégâts de la structure causés par l'explosion sont considérés. Les fenêtres et revêtements normaux ont cédé à une pression inférieure à 1 livre par pouce carré et, ce faisant, ont ménagé une décompression qui a limité la pression maximale développée, selon une formule simple. Sous une compression d'environ 30 livres par pouce carré, un mur creux se fissurera à environ 3,3 livres par pouce carré. Un mur de 4,5 pouces comprimé par des parois en retour a cédé à environ 5 livres par pouce carré, et un mur de 9 pouces, comprimé de même, a fissuré mais sans s'effondrer à 15 livres par pouce carré. Dans la simulation, avec aération normale, d'une situation domestique réelle, en vraie grandeur, il n'a été possible de ménager qu'une pression explosive à peine au-dessus de 3 livres par pouce carré. Une amplification possible des effets d'explosion due aux phénomènes de cascade ou de turbulence entre pièces communicantes est discutée brièvement et sera étudiée ultérieurement.

Key words: Building structures; damage; gas explosions; limiting pressures; load-bearing brickwork; venting.

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[1] Director of Research, Head of Heavy Clay Division and Chief Engineer, Heavy Clay Division, respectively.

1. Introduction

In May 1968 an explosion occurred in an 18th floor apartment of Ronan Point, a 22-storey precast concrete panel system building. The explosion blew out an external load-bearing flank panel, and progressive collapse of the floor and wall panels, right down to the podium, followed. An official enquiry concluded that the explosion was caused by town gas, and that explosions of this magnitude must be expected from time to time in domestic buildings. [1][2] Indeed, in Britain the statistics of gas explosions show that in the past decade the average annual rate has been rather less than 1 in 100,000 premises occupied and supplied with gas, and not more than 45% of the incidents recorded produced structural damage. Most of the brick buildings involved were low-rise, essentially non-loadbearing structures, and there is certainly no record of damage or collapse of a high-rise brick building.

An immediate consequence of the enquiry into the South London accident was the amending of the Government building regulations. [2] Essentially the amendments called for the provision of alternative paths to carry the load, assuming the removal of a critical section of the load-bearing walls, or to provide a form of construction of such stiffness and continuity so as to ensure the stability of the building against forces liable to damage the load-bearing members. The forces were assumed for this purpose to be equivalent to a standard static load of 5 lbf/in^2 (34.47 kN/m^2). The regulations cover all forms of construction, and so it was that the British Ceramic Research Association, as the main research agency of the British brick industry set out to examine the objectivity and relevance of the new regulations to structures in load-bearing brickwork.

2. The Project

The project called for facilities to determine the resistance to explosions of (a) normal types of fenestration and cladding (b) masonry walls and (c) a load-bearing masonry structure of full size. The explosions were to be based on town gas (roughly 27% methane and 45% hydrogen) or on natural gas (roughly 95% methane).

A leading brick company provideda site near a disused quarry at Potters Marston, Leicestershire. Old granite hoppers built of concrete consisting of two chambers, each about 19 x 10 x 7 ft. with one end open and the rear closed by 9 in. brick walls, provided facilities for "ranging shots" on the resistance of brickwork and various types of cladding.

The test building itself was designed to simulate the top three storeys of a tall cross-wall block and provides rooms with different venting characteristics. The brickwork is built in accordance with the B.C.R.A. Model Specification for Load-bearing Clay Brickwork [3], and the floors are in situ reinforced concrete.

The original objectives were to determine:

(a) the effectiveness of venting, or explosion relief, provided by cladding and windows;

(b) the pressures required to destroy cladding and windows;

(c) the pressure necessary to damage a load-bearing brick wall;

(d) the pressure-time profiles where practicable.

The present paper records the considerable degree of success achieved in reaching these objectives, but a fifth objective, to test the competence of the structure to withstand progressive collapse following the failure of a main structural wall was not achieved because the building though damaged remained entire.

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[2] Figures in brackets indicate the literature references at end of this paper.

3. Explosion Generation and Measurement

The Midlands Research Station of the Gas Council generated the gas explosions using both town and natural gas either in balloons filled with a stoicheiometric gas-air mixture, or as layered mixtures of gas and air.

Pressure recordings were made first by the Atomic Weapons Research Establishment, who used piezo-electric transducers and a tape-recorder transfer system from which the final pressure-time profile was presented graphically by way of galvanometer and ultra-violet recorder. A similar system was used in later experiments by the Midlands Research Station, and the Fire Research Station (Department of the Environment) participated in some later rounds with direct recording from quartz transducers on to a cathode ray oscilloscope.

A gas-air explosion is a comparatively slow event: the time of rise to peak may be of the order of 100 m.sec. and the whole pulse may occupy a few hundreds of milliseconds. The time scale is thus quite different from high explosive incidents when peak pressures are reached within milliseconds. Pressure-time profiles for fairly modest explosions with layered town gas and layered natural gas (fig. 1) illustrate not only the time scale involved, but also that natural gas produces a slower explosion than town gas.

4. Bunker Experiments

A complete brick cladding was provided by a 4½ in. common brick wall, with 1:4 cement sand mortar with plasticiser, returned 18 in. inside the bunker, so that there was substantial restraint. The wall was fully restrained at the top and bottom within the concrete bunker. Explosions were provided by balloon, and this wall withstood successive explosions at measured peak pressures of 1.4, 2.1 and 3.3 lbf/in^2 before being completely destroyed at 5.1 lbf/in^2.

A nine-inch solid wall, without returns, built up to the concrete of the bunker, withstood successive explosions of 5, 7.5 and 10 lbf/in^2 without damage and failed by a yield line crack pattern, without collapse, at about 15 lbf/in^2. A second, similar wall sustained nine successive explosions, reaching 7 lbf/in^2 without any damage whatever.

While the information from these experiments was encouraging and even impressive, it was not so important as the information to be derived from experiments involving windows and cladding, for it is upon these components that the venting of an explosion in a real building depends. The action of venting is first to provide a relief which will limit the pressure build-up within the explosion space, and then to provide an unrestrained escape for the burning gases. The relief is governed by the resistance of the vent closure, which can be simply glazing or may be a composite affair of doors, windows and panelling. A closure, or cladding, of this latter type is shown in figure 2: the geometry is summarised in Table 1 and the venting coefficients are those defined by Rasbash [4]

The complete door-window cladding failed at 1.0 lbf/in^2 produced by 9.7 cu.ft. of town gas with 2.5 cu.ft. of air in a balloon. The recorded pressures for nine transducers ranged from 0.65 lbf/in^2 to 1.45, with six values lying between 0.95 and 1.05 lbf/in^2.

The behaviour of the windows per se depends on the area and on the thickness of the glass, and in a British Code of Practice on the glazing and fixing of glass for building [5] recommendations are made which depend upon a glass factor, which is the area in square feet divided by the perimeter in linear feet ($=ab/2(a + b)$). From the results of tests [6] on both single and double-glazed windows it is possible to define values of pressure which do not break the glass and values which do, but of course the excess pressures in the latter case are not known. The explosion failure pressure broadly follows the recommendations of the Code of Practice so that double glazing raises the relief pressure by 50 to 100%. Glass more than a year old gave failure loads 20% less than new glass.

The relevance of these results to an actual situation depends upon the venting action. It has been suggested [4] that in a domestic scene the maximum pressure developed, P_m, is related to the pressure at which the vent opens, p_v, by an equation of the form

$$p_m = Ap_v + BK$$

where K is the ratio of the smallest cross-section of the room to the total area of explosion relief (the vent area coefficient). If K does not exceed 5, p_v does not exceed 1 lbf/in^2 and the weight of the vent cover does not exceed 5 lb per square foot of vent area, then $A \approx 1.5$, and B, which depends upon the fundamental burning velocity of the gas, is typically 0.5 for propane, 0.4 for methane and 1.3 for town gas. In the light, then, of the data obtained from the bunker experiments, it seems that, in the absence of modifying factors like excessive turbulence or cascade effects, it would be unlikely that a pressure as high as 5 lbf/in^2 could be reached in a normally vented building and indeed, as the work in the test building showed, this is the case.

5. The Test Building Experiments

The floor plan and wall details of the test building are shown in figure 3. The floors are in situ cast concrete, and are carried through to the outside of the outer leaf. The rooms are 8 ft. 4 in. high (actual), so that the volume of each room is rather more than 1000 cu.ft. The gable walls are 11" cavity construction i.e. two 4½ in. wythes separated by a 2 in. air gap, and tied together by metal ties embedded in the bed joints of the two wythes. Provision is made for various types of cladding and fenestration, some of which are illustrated in figure 4.

The calculated precompression on the cavity walls was 31 lbf/in^2.

Figure 5 shows the layout of transducers in Room 1 which had been closed by a complete window and door frame unit similar to that which had been tested in the bunker and which had failed at 1 lbf/in^2. Complete failure of this frame would give a K value of 1, so that, regardless of the amount of explosive mixture in the room, it was not anticipated that the peak pressure recorded would be much greater than 1 or 2 lbf/in^2. A balloon was used which, if no venting occurred, would produce a pressure of 5 lbf/in^2. The pressures measured in the ignition room (Room 1) ranged from 0.8 to 1.3 lbf/in^2, with a mean of 1.1 lbf/in^2. A following rarefaction wave reached a peak of 0.4 lbf/in^2, and this pulled in the communicating door between Rooms 1 and 2. In the second room three transducers all recorded a peak of 0.1 lbf/in^2.

No damage was caused to the brickwork. The windows and frame were ejected bodily from the front of Room 1 to a distance of about 15 ft., but the window in Room 2 remained intact.

A summary of further balloon rounds in the building is given in Table 2. It will be seen that although "no-relief" pressures as high as 17 lbf/in^2 were projected, the maximum pressure reached anywhere was only 1.9 lbf/in^2, with no damage to the brickwork, although the windows and cladding were blown out in every case, justifying the whole concept of venting.

The balloon experiments of course provide complete control on the amount of explosive mixture used, but in order to simulate a real accident, gas was piped into a room and allowed to percolate into the adjoining room. In some cases, the connecting door was open and in others closed. Walls, floors and ceiling were coated with a bitumen sealing paint and all obvious cracks around window frames were stopped up. The gas concentration was monitored by four probes arranged at different levels from floor to ceiling and connected to a gas chromatograph, and when the required situation was established, the mixture was electrically ignited. It was notably difficult to restrain the leakage of gas from the building in spite of the measures taken to prevent it, and indeed in one of the experiments although 425 cu.ft. of gas had been metered into Rooms 3 and 4 in 100 minutes, at the end of that time only 70 cu.ft. was available for ignition.

A summary of the observations of the first layered gas experiments is given in Table 3.

Three of these rounds caused no damage to the brickwork, but round 49 is of special interest. Here, 420 cu.ft. of town gas were piped into Room 2 through a ¾ in. hose in 20 min. when gas analysis showed an almost stoicheiometric mixture (20% gas by volume). The door to Room 1 was open, and ignition took place in this room, which had, for this experiment, been closed by a heavy cladding, incorporating cupboards and a working surface, similar to that in the London apartment.

A peak pressure of 1.3 $\mathrm{lbf/in^2}$ was reached in Room 1, 127 ms after ignition; 6 ms later 3.3 $\mathrm{lbf/in^2}$ was recorded at the centre of the outside cavity wall in Room 2, and the cine films showed that the first sign of damage to this wall appeared at 270 ms after ignition.

The damage caused by this explosion was considerable.

1. The large window in Room 2 was blown out.
2. The whole of the cladding in Room 1 - cabinets, window frame and glass - was ejected.
3. The outer leaf of the cavity wall nearest the bunker was cracked horizontally, with a vertical crack at each end, bowed out 6½ in. at the rear and 2½ in. at the front (fig. 6).
4. The inner leaf showed a clear pattern of yield-line cracking in each room, but these cracks were not open after the explosion.

The building as a whole showed no signs of collapse, but was propped and then sustained two further explosions (rounds 62 and 63) in Rooms 3 and 4, in one of which a peak pressure of 1.6 $\mathrm{lbf/in^2}$ was reached without extension of damage or weakening of the structure.

The circumstances of round 49 were manifestly of great interest. An "amplification" of pressure, by turbulence or cascade effect, had occurred as the explosion ripped from Room 1 to Room 2, and a pressure had been reached at which the brickwork had failed. A very detailed analysis of the whole incident was made and, although it is not possible to discuss this here, it is perhaps worthwhile to present the pressure time records (fig. 7). The glass yields and venting begins just after 100 ms: the cladding starts to move at about 180 ms and has gone by 330 ms, just after a vertical crack appears at one end of the gable wall and just about the same time as the great horizontal crack has fully developed.

It was decided to rebuild the damaged walls and to attempt to repeat round 49 as nearly as possible, to rule out the chance of a freak effect. The Fire Research Station (Department of the Environment) co-operated in this phase of the work.

About 420 cu.ft. of gas were metered into Room 2, giving a nearly stoicheiometric mixture there. The pressures recorded by the various gauges are marked in figure 8. The maximum pressure was 3.2 $\mathrm{lbf/in^2}$ compared with 3.3 $\mathrm{lbf/in^2}$ in round 49. Cladding and windows were destroyed, but the brickwork was virtually undamaged. At the corner of Room 2 there were two fine vertical cracks in the outer leaves near the junction with the rear wall and the 4½ in. partition wall was cracked where it joined the inner leaf.

In any series of experiments designed to simulate accidental effects it must be admitted that a real accident might occur, and indeed in a later ranging round in Rooms 3 and 4 an unexpected stoicheiometric build-up occurred, resulting in damage almost exactly duplicating that of round 49 ! A yield line pattern of cracks was developed on the front and gable walls but the horizontal crack developed at the rear closed up again.

Unfortunately, major recording facilities were not operational at this time and it can only be reported that the damage was caused by a peak pressure of about 3.5 $\mathrm{lbf/in^2}$. A general view of the damage is shown in figure 9 and it is interesting that the incidence of major damage in the various rounds seems to be bracketted within a range of 0.2 to 0.3 $\mathrm{lbf/in^2}$.

6. Conclusion

The experiments described in this paper have, in effect, achieved the objectives set out. Normal windows and cladding will fail at pressures below 1 lbf/in^2 and in so doing they provide venting relief which limits the maximum pressure developed roughly in accord with a simple formula. It has been shown that under a precompression of about 30 lbf/in^2 a cavity wall will crack at about 3.3 lbf/in^2. A 4½ in. wall fully restrained by returns within the concrete bunker opening failed at about 5 lbf/in^2 and a 9 in. wall cracked but did not fail at 15 lbf/in^2 when fully restrained.

In a normally vented simulation of a full-scale real domestic situation, it has not been possible to raise an explosion pressure greater than just over 3 lbf/in^2, even in a most contrived situation with gas pouring in at the rate of over 400 cu.ft. in twenty minutes (it was estimated that in the London explosion only 50 cu.ft. of gas were involved). Although a pressure of this magnitude may crack an 11 in. cavity wall under the order of precompression normally existing two or three storeys down in a high rise block, a brick masonry building of the type described has shown no tendency to complete collapse.

While the competence of brickwork and the effectiveness of venting have been very satisfyingly demonstrated in these experiments, which are the first of their kind carried out in a real structure, it must be stressed that the work has exposed an area of uncertainty about the possible amplification of explosion effects due to cascade or turbulence in a system of interconnected rooms. This will receive careful and systematic study by the Fire Research Station, for at Potters Marston, as has been repeatedly stressed, it has been possible only in the most contrived situation to reach a pressure capable of damaging the main fabric of the brick building, in spite of exposure to a series of non-destructive explosions both before and after the major incidents.

7. Acknowledgements

The financial support for these experiments was provided by the British brickmakers through the Brick Development Association, by the Gas Council through the services of the Midlands Research Station, and, in the last phase, by the Department of the Environment. The technical support provided by the Atomic Weapons Research Establishment was of the highest order, and is gratefully acknowledged. The authors are greatly indebted to their architectural and engineering colleagues, notably Mr. Donald Foster of Structural Clay Products, Ltd. and Mr. Barry Haseltine of Jenkins & Potter, Consulting Engineers, for advice at all stages of the project. Finally the authors record their thanks to the Council of the British Ceramic Research Association for permission to present this paper.

8. References

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[2] "The Building (Fifth Amendment) Regulations 1970", London, H.M.S.O. 1970.

[3] "Model Specification for Load-Bearing Clay Brickwork", British Ceramic Research Association, Special Publication 56, 1967.

[4] Rasbash, D.J., "The Relief of Gas and Vapour Explosions in Domestic Structures" Structural Engineer, 47, (10), 404, 1969.

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Table 1. Venting Characteristics of Cladding in Bunker

Component failing	Vent Area (ft^2)*	Venting coefficient
Total Cladding	65.75	1.0
Glass:		
Total	27.3	2.4
Large and Medium windows only	15.5	4.2
Chipboard	12.6	5.2

* 1 ft^2 = 0.093 m^2

TABLE 2 - DATA FROM BALLOON EXPLOSIONS IN THE MAIN BUILDING

Round No.	Gas	Ignition in room No.	Nominal pressure (lbf/in^2)*	Measured pressures (lbf/in^2)* for individual transducers†		Ignition room		Second room	
				Room in which ignition occurs	Second room	Max pressure (lbf/in^2)*	Time to peak (ms)	Max pressure (lbf/in^2)*	Time to peak (ms)
22	T	1	5	B1 B2 B4 B5 C1 C2 C4 C5 D1 D2 D4 D5 1.02 0.8 1.2 1.14 1.19 1.1 0.99 1.3 0.98 1.0 0.98 1.06 F1 F2 F4 F5 E1 E2 E4 E5 1.0 1.09 0.99 1.07 1.07 1.11 1.09 1.09	F1 F2 F3 0.1 0.1 0.1	1.3	55	0.1	55
30	M	1	16	Misfire					
31	M	1	17	B1 C3 D1 F3 0.28 0.39 0.27 -	C1 X3 Z1 F3 0.09 - 0.07 -	0.4	100	0.1	140
36	T	1	16	B1 C3 D1 F3 1.46 1.92 1.66 [illegible].71	C1 X3 Z1 F3 - 0.45 0.40 0.40	1.9	120	0.5	151
23	T	4	12.5	F1 F2 F4 F5 - 1.91 1.71 1.81	F1 F2 F4 F5 1.40 1.44 1.61 1.6	1.9	45	1.6	55
32	M	4	16	X3 C5 Z3 F3 0.78 0.8 - 0.83	A4 B3 C3 F3 D1 0.41 0.4 0.58 0.61 0.26	0.8	600	0.6	510
41	T	4	16	X3 C5 Z3 F3 1.47 1.63 1.5 1.56	A4 B3 C3 F3 D1 0.69 0.75 0.68 0.72 0.86	1.6	140	0.9	165

* 1 lbf/in^2 = 6.895 kN/m^2
† See Figures 18 and 19 for locations. All positions noted from front of building.

Table 3. Data from layered gas experiments in the main building

Round	Gas	Ignition Room		Second Room	
		Max. Press. lbf/in^2	Time to Peak ms	Max. Press. lbf/in^2	Time to Peak ms
46	N	0.7	410	0.7	425
49	T	1.3	126	3.3	133
62	T	1.0	160	0	-
63	T	1.1	150	1.6	160

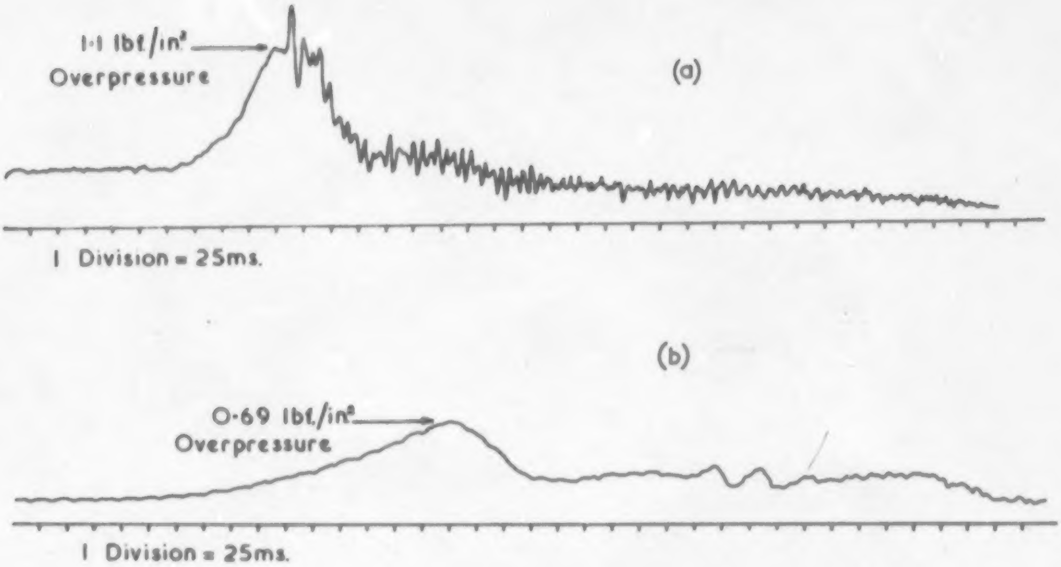


Fig. 1 Pressure/time profiles for (a) layered town gas (round 63) and (b) layered natural gas (round 46)

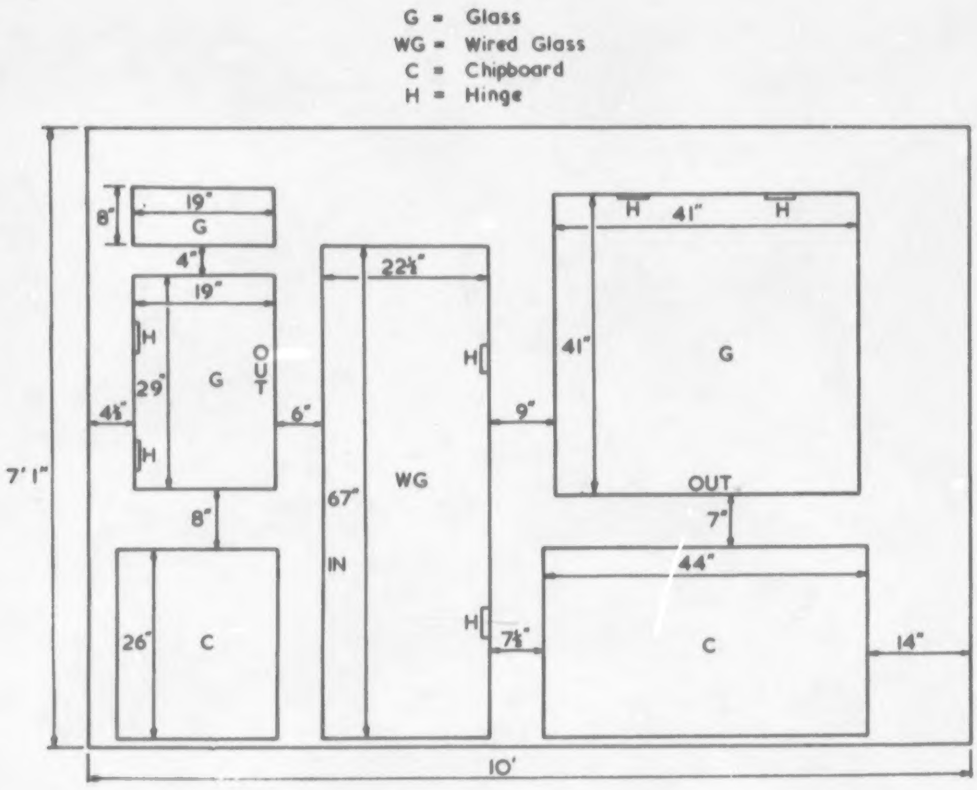

G = Glass
WG = Wired Glass
C = Chipboard
H = Hinge
8"
19"
G
4"
19"
H
29"
G
OUT
H
4½"
6"
8"
26"
C
22½"
H
67"
WG
IN
H
7½"
9"
H
41"
H
41"
G
OUT
7"
44"
C
14"
7' 1"
10'

Fig. 2 Details of cladding used in left-hand bunker

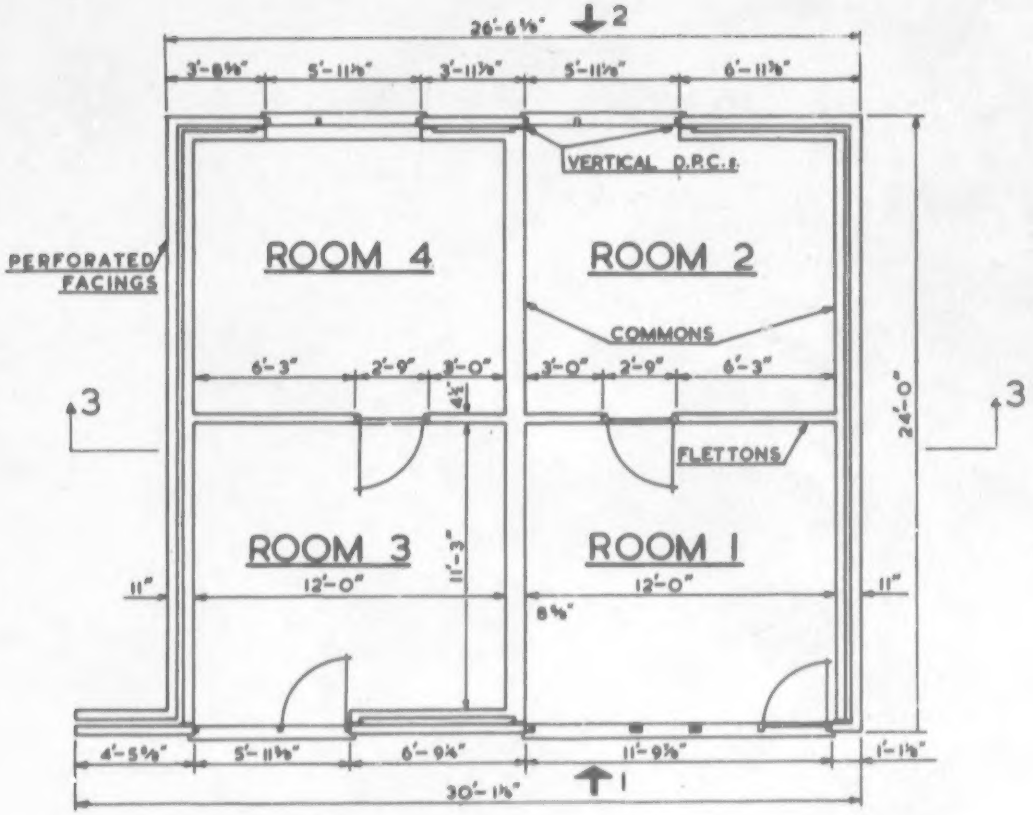

26'-6⅛"
2
3'-8⅝"
5'-11⅛"
3'-11⅞"
5'-11⅞"
6'-11⅜"
VERTICAL D.P.C.s
PERFORATED FACINGS
ROOM 4
ROOM 2
COMMONS
6'-3"
2'-9"
3'-0"
3'-0"
2'-9"
6'-3"
4½"
3
3
24'-0"
FLETTONS
ROOM 3
ROOM 1
11'-3"
11"
12'-0"
12'-0"
11"
8⅝"
4'-5⅝"
5'-11⅛"
6'-9¼"
11'-9⅞"
1'-1⅛"
1
30'-1⅛"

Fig. 3 Test building, floor plan and wall details

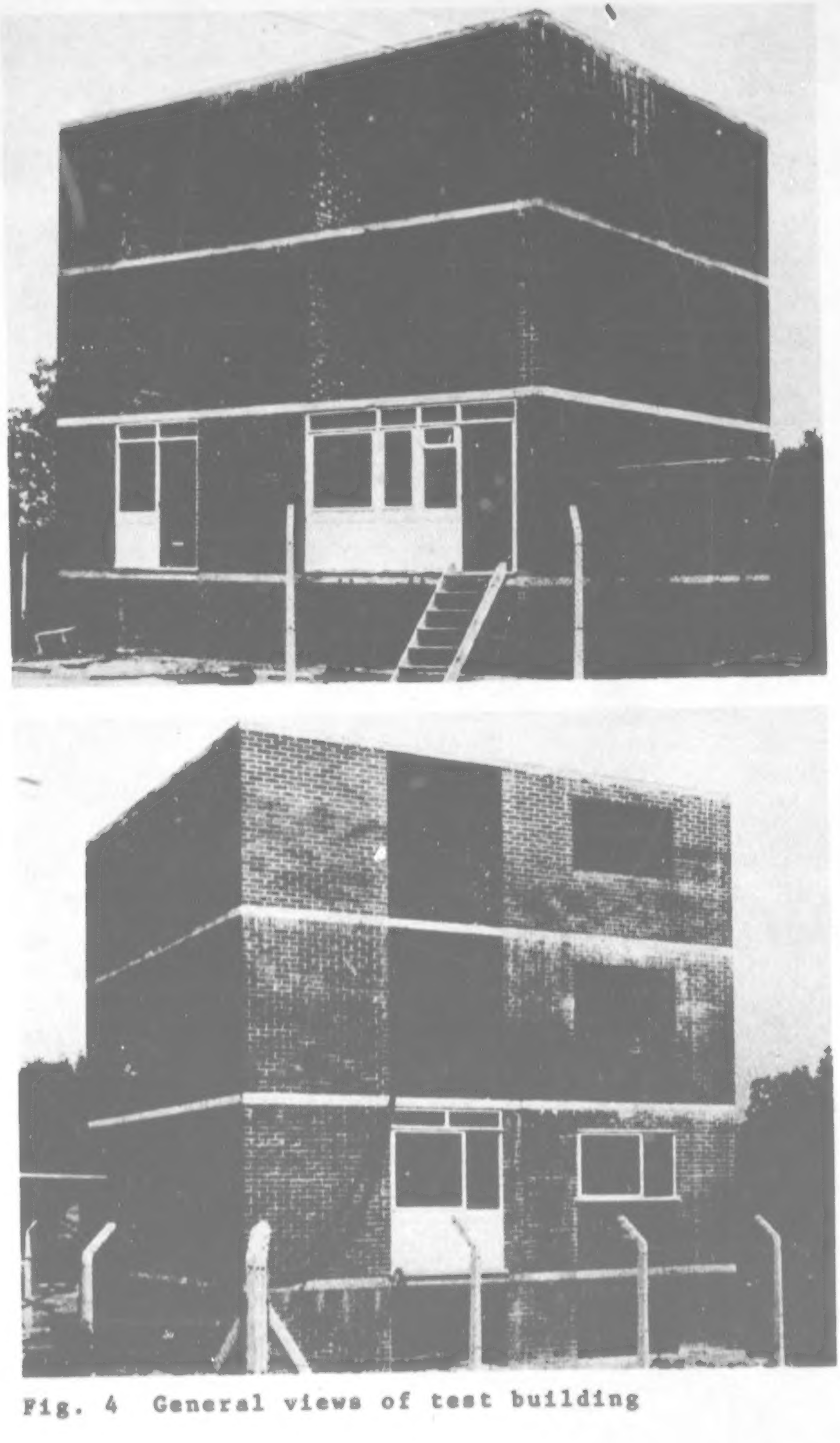


Fig. 4 General views of test building

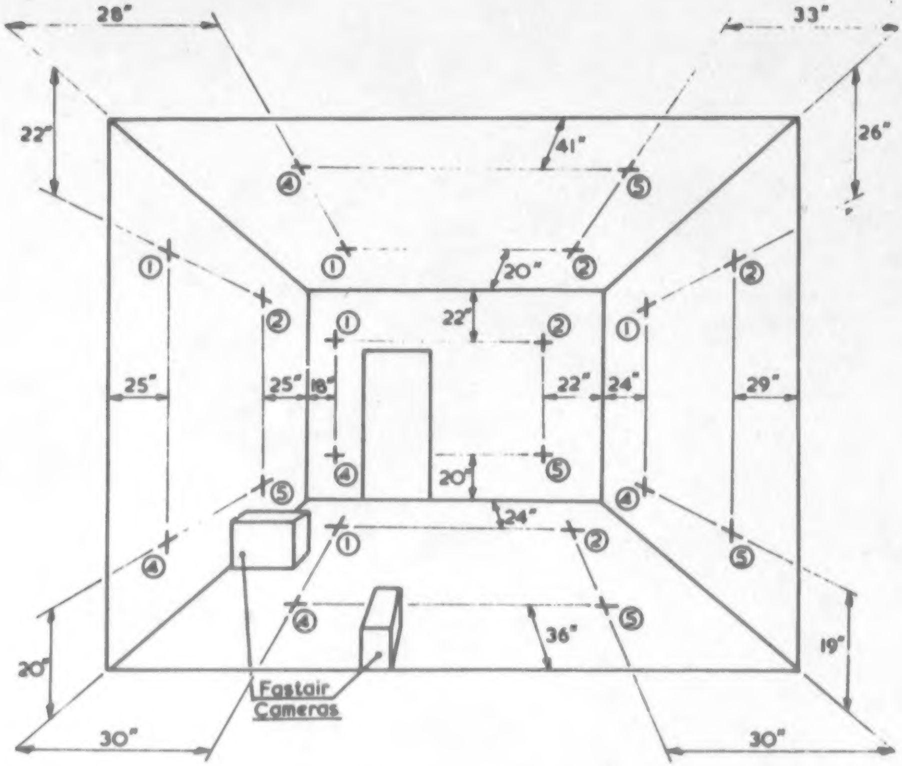

28"
33"
22"
26"
41"
④
⑤
①
①
20"
②
②
②
①
22"
①
②
①
25"
25"
18"
22"
24"
29"
④
20"
⑤
⑤
④
24"
①
②
④
⑤
④
36"
⑤
20"
19"
Fastair
Cameras
30"
30"

Fig. 5 Room 1 viewed from front of building (vent wall) showing transducer layout for main experiment, round 22

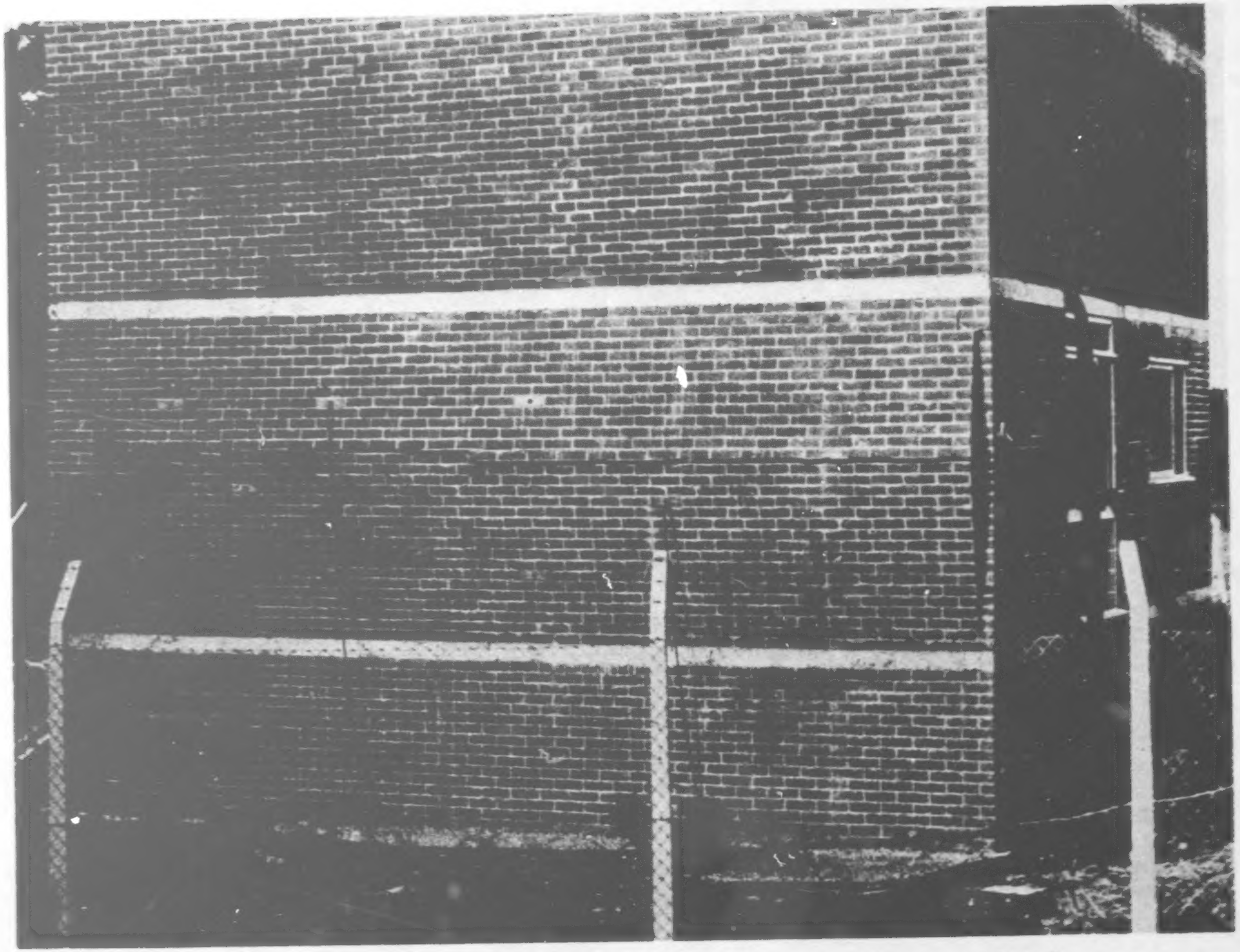
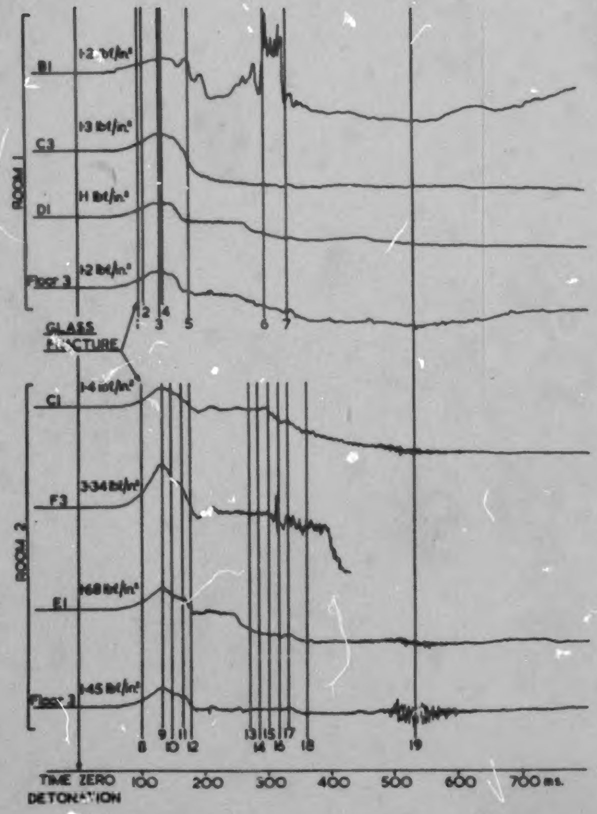


Fig. 6 Round 49: damage to outer leaf of gable wall of Rooms 1 and 2, showing large vertical crack at rear



SEQUENCE OF EVENTS: ROUND 49

Room	*Event*	*Time from zero (ms)*	*Detail*
1	1	95	Glass begins to fracture
1	2	104	(a) Window frame begins to fall out (b) Venting to floor above
1	3	127	Peak overpressures recorded
1	4	133	Window frame falls out
1	5	178	Cladding begins to move
1	6	298	Vertical crack appears
1	7	334	Cladding falls out
2	8	100	Glass begins to fracture
2	9	133	Peak overpressures recorded
2	10	146	Cladding begins to break
2	11	162	Cladding begins to lift up from lower edge
2	12	177	Cladding separates from wall, moving gas pipes with it
2	13	270	(a) Vertical crack in wall X (b) possible horizontal crack in wall Y (c) gas burning near ceiling (d) cable at X3 bowed towards wall
2	14	286	(a) Horizontal crack in wall X appears (b) horizontal crack in wall Y appears (c) volume of gas burning increases (d) upper end of cable X3 moving rigorously (blurred in photographs) (e) cable B3 bowed towards wall
2	15	301	(a) Horizontal crack in wall X extends (b) horizontal crack in wall Y extends (c) further increase in volume of gas burning (d) cable movement, upper end of X3 bowed outwards
2	16	317	(a) Extension of horizontal crack in wall X3 leading to next course (b) horizontal crack in wall Y closing (c) cable of X3 upper end bowed outwards - possible straining of cable
2	17	332	(a) Horizontal crack in wall Y is closed (b) length of exposed X3 cable increases possibly because pressure transducer moved backwards in its mounting at this stage
2	18	363	Cable B1 also seen to bulge out across horizontal crack
2	19	480 to 625	Transducers affected by debris and heat

Fig. 7 Pressure/time records for round 49

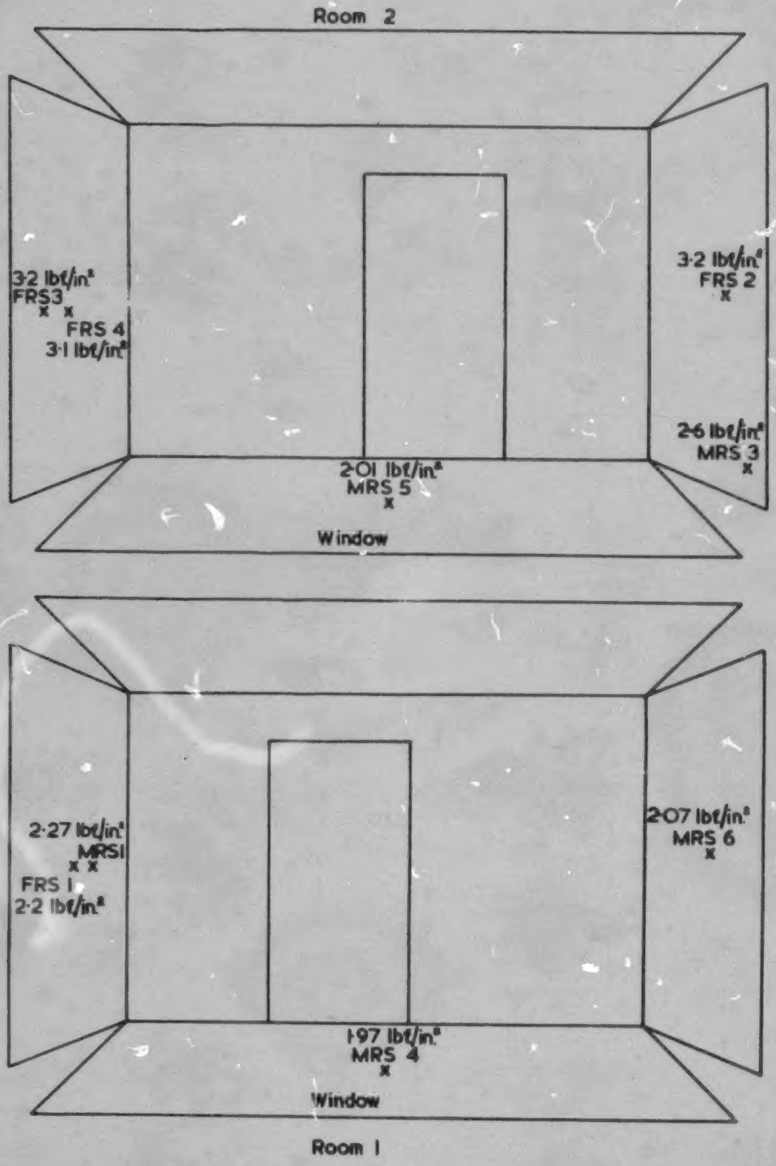

Room 2
3·2 lbf/in²
FRS3
FRS 4
3·1 lbf/in²
3·2 lbf/in²
FRS 2
2·6 lbf/in²
MRS 3
2·01 lbf/in²
MRS 5
Window
2·27 lbf/in²
MRS1
FRS 1
2·2 lbf/in²
2·07 lbf/in²
MRS 6
1·97 lbf/in²
MRS 4
Window
Room 1

Fig. 8 Positions of transducers, round 14

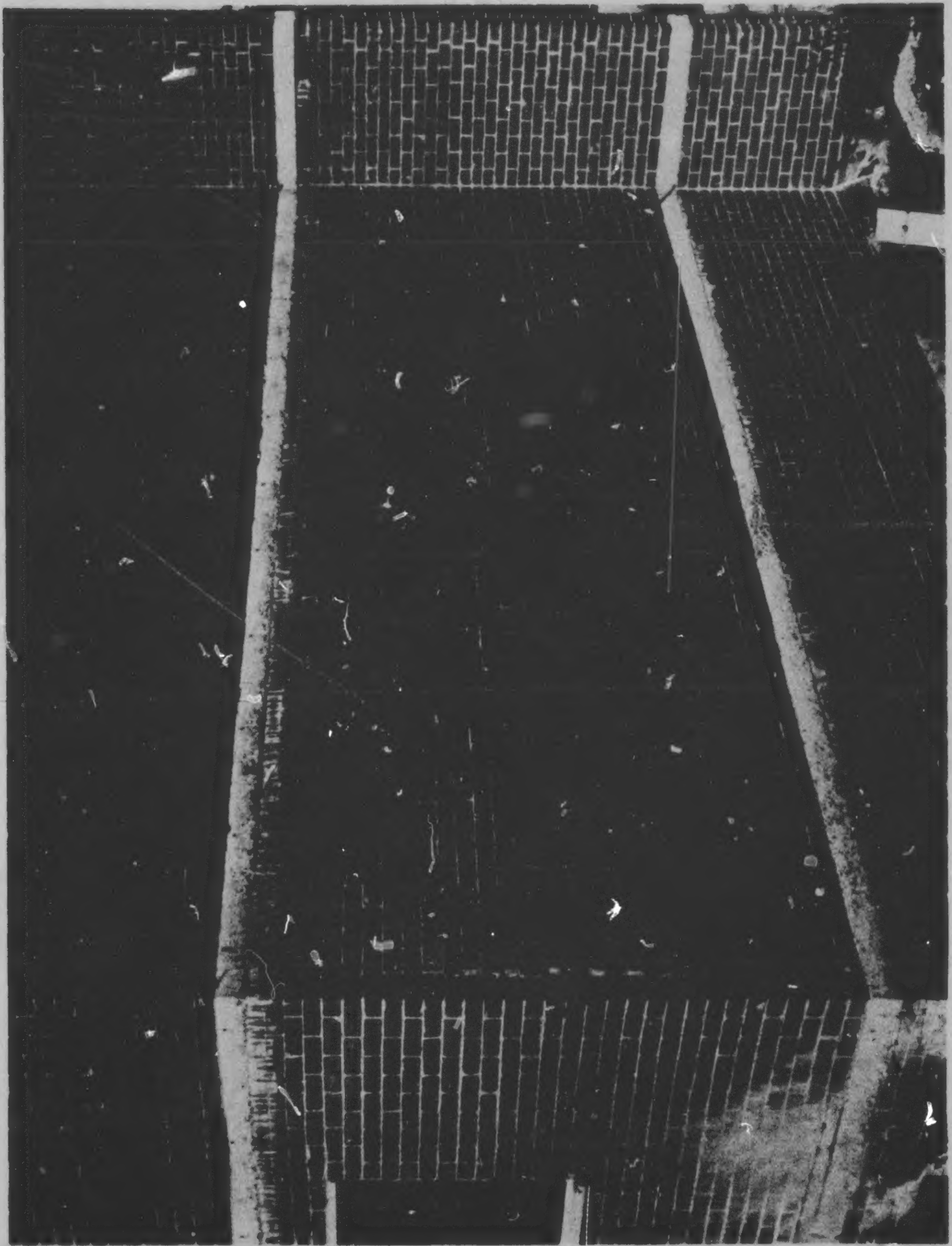


Fig. 9 Damage in final round, Phase IV

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Performance Characteristics for Timber Frame Joist Floors

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Different loads which act on a floor are discussed and a factor of safety based on economic criteria is used. The paper also discusses vibration and deflection criteria for timber frame joist floors.

It is pointed out that the deflection under a single point load may be used as a performance criterion for human perception to initial vibration.

An acceptable strength and deflection performance of a wood-joist floor systems is given.

Key words: Dwelling, floor (wood), deflection (floors), loads, strength (floors) vibration (floors), joists, performance criteria.

On examine différentes charges qui agissent sur un plancher. Fondé sur des critères économiques, un facteur de sécurité est employé. La communication discute aussi des critères de vibration et de fléchissement pour les planchers de solives de bois.

On montre que le fléchissement dû à une charge ponctuelle peut être utilisé comme critère de performance pour la perception humaine d'un début de vibration.

On indique une performance acceptable pour la résistance et le fléchissement d'un système de plancher de solives de bois.

Key words: Deflection (floors); dwelling; floor(wood); joists; loads; performance criteria; strength(floors); vibration(floors).

Notations

A	part of the construction cost which is independent of the factor of safety
B	part of the construction cost which is assumed to be proportional to the factor of safety
C	construction cost
p	ultimate single point load
R	cost of repair and inconvenience in case of failure
T	total cost
a	amplitude
f	frequency
k	factor of safety
$\ln$	natural logarithm
q	uniform distributed load
r	ratio of real strength for given load duration to testing strength
s	standard deviation
t	time
y	deflection
α	a factor which is the ratio between the movement of the top of furniture and the deflection of a floor
δ	**logarithmic decrement of a damped vibration**
ε	probability of failure
μ	standardized variable in the normal disbribution
σ	coefficient of variation or standard deviation of ln k which is approximately the coefficient of variation of k

1. Introduction

In order to develop performance requirements and characteristics for building hardware one may follow two main approaches.

- One approach is to start with process of use, activities and user characteristics, trying not to be limited by traditional concepts of possible solutions.
- The other approach is to abstract the functional requirements from existing solutions.

In this case the possible solution is restricted to a timber frame joist floor for dwellings. The second approach, therefore, seems to be a natural choice to develop the performance characteristics.

A proposal for a list of headings characterizing important properties of a building element as a floor will not be put forward in this paper because the CIB Working Commission No. 31 plan to present such a list at the end of 1971.

The paper will limit its discussion of performance characteristics to problems related to bearing capacity, deflections and vibrations.

2. Bearing capacity

2.1 Loads

The loads are defined as the mean most unfavourable loads which will occur in the building during its **lifetime** by normal use.

From this definition it follows that the dead loads should be calculated from the mean specific gravity of the materials. The specific gravity of wood will change with changing water content. In determining the specific gravity of wood, water content equal to the mean most unfavourable value should be chosen.

Live loads in dwellings consist of furniture and people. The live load may also be defined as the highest permitted load on the floor. The permitted load must, however, be chosen in such a way that as few restrictions as possible are put on the use of the floor, i.e. there should be no restrictions on "normal use" of the floor. Normal use is, however, a very vague phrase, and it is necessary to explain in a more specific way what the phrase involves.

Usually live loads are divided into two types according to loaded area

a) Distributed loads
b) Single point loads

The distributed load used in calculations, very often called nominal distributed load, is usually an equivalent distributed load which has the same load effect as the real load.

In most building regulations the nominal live load in dwellings is taken as 150 kpm^{-2} (1500Nm^{-2}) or 200 kpm^{-2} (2000 Nm^{-2}). As a live load of 150 kpm^{-2} (1500 Nm^{-2}) has been used in many countries for a long time without serious complaints, that load seems to be sufficient for normal use. A live load of 200 kpm^{-2} (2000 Nm^{-2}) assures a quality which most users will not gain advantage from, and such a quality can only be justified if it involves only a small extra cost. Note: 1 kp = 1 kilogram force.

Statistical surveys of live loads in dwellings usually show much lower loads than 150 kpm^{-2}. An investigation by Arne Johnson (1)[1] shows that the mean most unfavourable loads, q, in Swedish dwellings during a 10 years period were:

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[1] Figures in brackets indicate the literature references at the end of this paper.

due to persons $\bar{q} = 30$ kpm^{-2} (200 Nm^{-2}) standard deviation s = 15 kpm^{-2} (150 Nm^{-2})

due to furniture $\bar{q} = 27$ kpm^{-2} (270 Nm^{-2}) " " s = 5,2 " (52 Nm^{-2})

Taking the sum of these loads (which is an assumption on the safe side because these two loads are not independent), one gets:

$\bar{q} = 57$ kpm^{-2} (570 Nm^{-2}), standard deviation 16 kpm^{-2} (160 Nm^{-2}).

Even by correcting for several changes of occupancy, the live load according to his investigation would be far less than 150 kpm^{-2}. In timber frame joist floors, usually criteria other than strength determine the dimensions so that a reduction in the normal dead load normally would lead to only small savings in cost, if any.

For timber frame joist floors, single point loads are of special interest. These single point loads are either long time loads (from furniture) or short time and dynamic loads (mostly from people jumping or dropping heavy items on the floor).

1. Book-case. If 6 shelves with span of 1,2 m and load of 40 kpm^{-1} (400 Nm^{-1}) per shelf is assumed, the total weight will be:

   $$6 \cdot 1{,}2 \cdot 40 = 290 \text{ kp } (2900 \text{ N}).$$

   The book-case rests on 4 legs i.e. 290/4 = 75 kp per leg. (750 N)

2. A large piano weighs about 200 kilos and rests on 4 legs, i.e. 50 kp per leg (500 N).

3. A large concert piano weighs about 400 kilos and rests on 3 legs, i.e. 133 kp per leg (1330 N).

4. A large refrigerator (for home use) weighs, with contents, about 200 kilos and rests on 4 legs, i.e. 50 kp per leg (500 N).

From these few examples it seems reasonable to assume that a long time single point load of 100 kp should be sufficient in most cases. With only 100 kp permitted as a long-time single-point load, some restrictions would be put on the use of the floor (a large concert piano and a large safe would be too heavy). For other reasons (see below), however most floors will be able to carry heavier loads.

The dynamic load from jumping will differ from person to person. When a man jumps, he reaches the ground at a certain velocity and the damping effect will depend on the strength of the leg muscles. Forces up to 250 kp (2500 N) have been observed in stairs. The duration of such a force is usually very short, probably less than 1/2 second.

An assumption of a single point load of 250 kp (2500 N) with a duration of 1/2 second seems to be reasonable.

Some standards describe a test with a falling sandbag on the floor. The dynamic response from a man who jumps is however quite different from a falling sandbag, and it is questionable if this test gives better results than a static test.

For a wooden floor, a long time load of 100 kp (1000 N) is equal to a test load of 100/0,6 = 167 kp (1670 N). A load of 250 kp with duration of 1/2 second will give a test load of about 250/1,2 = 208 kp (2080 N). In the case of a wooden floor the longtime load can therefore be increased without extra cost.

2.2 Strength

In calculating the necessary dimensions, safety factors or permissible stresses are taken from various codes or standards. The safety level will thus be independent of how serious the effect of a failure is. The results of a failure, however, of a beam and a subfloor may be quite different. In the first case the whole floor may fall down and the damage is difficult to assess. It may even involve loss of life. In the latter case the damage is more predictable. It will involve repair, inconvenience and/or possibly a broken leg.

We may postulate that in cases where the damage is small and predictable, a safety factor which **minimizes** the total cost should be used. If the cost of construction is $C = A + kB$ (A and B are constants and k is the factor of safety), R the cost of repair and inconvenience in case of failure and ε the probability of failure, then the total cost $T = A + kB + \varepsilon R$ should be a minimum. Under certain assumptions, the safety factor k can be calculated from the given equations. As a result of such calculations, which are based on the assumption of $R/B = 100$, and ln k having a normal distribution, the safety factors obtained are:

$\sigma_k = 0{,}10$	$k = 1{,}4$
$\sigma_k = 0{,}15$	$k = 1{,}61$
$\sigma_k = 0{,}20$	$k = 1{,}86$
$\sigma_k = 0{,}25$	$k = 2{,}10$
$\sigma_k = 0{,}30$	$k = 2{,}35$

where $\sigma_k = \sqrt{\sigma_1^2 + \sigma_2^2}$ and σ_1 and σ_2 are the coefficients of variation for the load and the strength respectively.

Very often the strength of a floor for single point loads is determined by testing. Such a test is usually performed with a steel disk of 25 mm diameter. This area of loading seems to agree well with that from furniture, but is too small compared with the foot of a man. In the case of wood floors, the size of the loaded area does not seem to be critical. Therefore, the steel disk can be used in both cases. The strength requirement for a timber joist floor can be summarized as follows:

1. The floor shall carry a distributed load of 150 kpm^{-2} (1500 Nm^{-2}) with sufficient safety i.e. the same safety level as used in construction in general.

2. The beam shall carry a single point load of 100 kp (1000 N)(long time load) and 250 kp (2500 N) (load with duration 1/2 sec.) with an economic safety.

Average ultimate single point load $\bar{p} \geq k \cdot \dfrac{100}{r_1}$ (1)

" " " " " $\bar{p} \geq k \dfrac{250}{r_2}$ (2)

Where r_1 and r_2 are factors which depend upon the duration of the load i.e. the ratio of real strength for a given load duration to testing strength and k is the factory of safety. If e.g. several tests are made on a subfloor and coefficient of variation of 20% and 10% are assumed for strength and load, respectively, then $\sigma_k = \sqrt{0{,}2^2 + 0{,}1^2} = 0{,}224$. For a wooden floor the required mean strength would be

$$\bar{p} \geq 1{,}98 \cdot \frac{100}{0{,}6} = 333 \text{ kp } (3300 \text{ N}) \quad (3)$$

$$\bar{p} \geq 1{,}98 \cdot \frac{250}{1{,}2} = 414 \text{ kp } (4140 \text{ N}) \quad (4)$$

One may compare this requirement with the requirement valid in Norway p.t.:

$$\bar{p} \geq \frac{150}{1 - \mu s} \frac{k_3}{r_1} = 150 \frac{1{,}3}{(1-1{,}64 \cdot 0{,}20)0{,}6} = 485 \text{ kp } (4850 \text{ N}) \quad (5)$$

In this case k_3 is a factor of safety chosen equal to 1,3 and μ is the standardized variable for the 5% fractile in a normal distribution.

3. Deflections and Vibrations

The deflection of timber frame joist floors is restricted for several reasons. The table below gives a general view on the subject

Reason for restricting deflections	Requirement imposed by		
	Materials in the floor	Use of the floor	Other building components
1. Damage to other building components			x
2. Damage to floor coverings and ceilings	x		
3. Annoying deflections		x	
4. Annoying vibrations	(x)	x	
5. Aesthetic considerations		x	

The deflection of the floor under live load shall not be so large as to cause damage to other building components. Other building components are mainly partition walls. The types of partition walls which are going to be used should be known before the deflection requirements are fixed. When the partition walls are constructed, usually the dead load already is acting on the floor. It is therefore mainly the live load which causes deflections although creep has to be taken into consideration.

Very stiff floor coverings and ceilings may be damaged under excessive floor deflection. The radius of the curvature is here the important criterion.

Annoying static deflection may occur when the sag of the floor exceeds certain limits. Usually it is not the deflection itself which causes inconvenience, but the deviation from a horizontal plane. As the angle at the support is a function of y/l (y is the deflection at the middle of the span and l, the length of the span), limits for y/l should be fixed. Usually a range of 1/240 to 1/300 is accepted as limiting values for the sag.

A special case is deflections caused by a moving live load. The moving load causes a change in deflection and therefore a change in angle at support. The change in angle may cause anxiety due to movement of tall furniture. That means that the floor should not have a deflection more than 1/300 to 1/400 of the span for a single point load of 100 kp (1000 N).

If the subfloor deflects too much, it will create an uneasy feeling when walked over. Because the span of subfloor is short (and therefore its natural frequency is high) and a substantial damping is present, this uneasy feeling is not related to uncomfortable vibrations. It is rather a feeling that the subfloor is unsafe. In Norway, the deflection of the subfloor is limited to 2 mm when loaded with a single point load of 100 kp (1000 N). This limit has been found by investigation of existing subfloors which are deemed to be satisfactory.

Annoying vibrations are often present in wood joist floors. These vibrations occur in the whole floor and are therefore dependent of the stiffness of the beams. An investigation made several years ago (2) concluded that if the deflections of the beams were less than 0,9 mm when loaded with a single point load of 100 kp (1000 N), only a small minority (about 10%) would find the floor to have uncomfortable vibrations. The result that y rather than y/l was a measure of the degree of annoying vibration was contrary to expectation.

It is known that the effect of vibrations on human beings may be a function of af where a is the amplitude and f the frequency. Reiher and Meister (3) found, for steady state vibration (amplitude a in μm, f in sec $^{-1}$).

$af < 50$	vibration	not perceptible
$50 < af \cdot 150$	"	just perceptible
$150 < af \cdot 420$	"	clearly perceptible
$420 < af$	"	annoying

The vibrations which occur in a floor are not steady state vibrations, but vibrations which decay with time. It has been discovered in recent years that if the vibration within a certain time decay period has a value which is just perceptible, it cannot be characterized as annoying. That means that the requirement would change to

$$ae^{-t\delta f} \cdot f < 150.$$

where δ is the logarithmic decrement and t is the elapsed time of inperceptible vibration.

It can be shown by mathematical calculations that if the weight of a man (the man is supposed to be the source of the vibrations) is large compared to the weight of the floor, the product af is a function of the deflection y from a single point load, but if the weight of the man is small compared to the weight of the floor, af is a function of y/l. That means that for short spans (and light floors) the deflection y is a good measure for vibration, while for floors with long span (and heavy floors) y/l should be the best measure. This postulate has been confirmed by a new examination of the results given in the investigation mentioned previously (2).

The general requirement to avoid annoying vibrations should be given by

$$y \cdot e^{-t\delta f} \cdot f < B \qquad (6)$$

where y is the deflection for a single point load, say 100 kp (1000 N), f the natural frequency in sec.$^{-1}$ and δ the logarithmic decrement of the floor. Constants t and B have to be evaluated by investigating existing floors. Such an investigation is planned in Norway, but has not yet started.

The direct effect on people is not the only cause of inconvenience by a vibrating floor. The vibration can be transformed to furniture and cause an uncomfortable noise (e.g. by glasses in a cupboard). This means that the acceleration should not be greater than the acceleration of gravity i.e.

$$af^2 \quad g \qquad (7)$$

Again the damping Plays an important role, and the requirement may be changed to

$$\alpha ye^{-t\delta f} f^2 \quad g \qquad (8)$$

where α is the ratio between the movement of e.g. furniture and the deflection of the floor and y is the amplitude caused by a walking man. If a beam with span l and with a single load in the middle of the span has a deflection y, then the angle, β, at support of the beam will be $\beta = 3\ y/l$. If the height of the furniture is h, then the movement of the top of the furniture will be $h \cdot 3\ y/l$ i.e. $\alpha = 3\ h/l$.

4. Conclusions

The design live load on timber frame joist floors should be

150 kpm^{-2} (1500 Nm^{-2}) distributed load
100 kp (1000 N) long time single point load
250 kp (2500 N) short time (½ sec.) single point load

2. In determining the dimensions of the beams, a safety factor should be used which is common in construction in general.

3. In determining the dimensions of the subfloor, a safety factor which **gives** a cost minimum should be used.

4. Partition walls, stiff floor coverings, and ceilings may often impose restrictions on the deflection of the floor. The type and nature of these building components should therefore be known before deflection limits are fixed.

5. The deflection under live load (distributed load) should not exceed $y/l = 1/240 - 1/300$.

6. The deflection of the beams under a single point load of 100 kp (1000 N) should not exceed $y/l = 1/300 - 1/400$.

7. Vibration should be limited by the following equations:

$$y_1 e^{-t\,\delta f} f \leq B$$

$$\alpha y_2 e^{-t\,\delta f} f^2 \leq g.$$

The constant t and B still need to be determined; y_2 is the deflection caused by a walking man and α is a factor which depends of the span and the height of cupboards.

The criteria given above express an average quality. They may be made more severe for better quality floors.

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(3) Reiher, H.J. and Meister, F.J. (1931) Human sensitivity to vibration. Forsch. aus dem Geb. des Ing. 2, 11, 381-6 (Transl. Rep. F - TS - 616 - RE, Wright Field 1946).

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Performance Requirements for Floors

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Several properties of floors and floorings have been studied. Test methods have been used which allow comparisons between different types of floor materials and floor constructions. On the basis of tests on actual floors and in the laboratory, classified performance requirements are proposed.

The validity of the properties for different floorings and subfloors is considered. Typical quality classes of actual floors are surveyed. Suggestions for performance requirements for the discussed properties of floors in dwelling-rooms are made by way of an example.

With the users' requirements and the future conditions in mind, relevant performance requirements can be chosen for different projects with the help of the paper. The intended quality of a floor can generally be obtained in more than one way. However, none of the alternatives fulfils all requirements. Extremely high requirements on certain properties often must be combined with low requirements on other properties for the same floor. Already extremely high requirements on two antagonistic properties - like resistance to indentation and warmth to touch - might result in the elimination of almost all floors or floorings.

On a étudié diverses propriétés des sols et revêtements de sols. Les méthodes d'essai employées ont permis de comparer différents types de matériaux de sol et de constructions de planchers. On propose des exigences de performance classées d'après des résultats d'essais sur des sols réels et sur des éprouvettes de laboratoire.

Les propriétés de différents revêtements de sol et garnitures sont vêrifiées, et l'on donne un aperçu des classes de qualités typiques des sols réels. A titre d'exemple, on a groupé quelques suggestions relatives aux exigences de performance pour les propriétés des planchers d'appartement.

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[1] Building Engineer

Si l'on ne perd pas de vue les demandes de l'usager et si l'on tient compte de l'imprévisible, on peut choisir pour différents projets, à l'aide de ce rapport, les exigences de performance pour les propriétés concernées. La qualité désirée d'un plancher peut généralement être obtenue de plus d'une façon. Cependant, aucune solution ne satisfait toutes les exigences. Souvent, il faut combiner des exigences strictes pour certaines propriétés avec, pour d'autres, des exigences moindres. On peut envisager que des exigences strictes pour deux propriétés antagonistes - comme la résistance à l'empreinte et la douceur au toucher - excluent tant de planchers et de revêtements que le reste pourrait ne pas être accepté pour d'autres raisons.

Key words: Colour fastness; flatness; flooring; indentation; performance requirements; properties; quality classes; rolling load; surface evenness; test methods; warmth to touch.

1. Preface

The need for performance requirements for building elements has been discussed in several reports. Unfortunately there are few such systems which can be used in construction programs or specifications for buildings. In Scandinavia performance analysis has been applied extensively especially on flooring, e.g. by Sneck, Bring, Lossius, Malmstedt, Nielsen and Schjödt (1)[2] and by Bring (2).

2. Introduction

Since there are no generally accepted definitions, I shall explain briefly my terminology.

A building element in use behaves under certain conditions which follow from its properties and from the affecting factors. The user (and often the authorities) has certain requirements for a building element. A performance analysis gives the corresponding properties, possibly in the form of a check list. The user's requirements are based on considerations of performance, appearance and economy. On the basis of the check list it is possible to express the performance requirements.

Similarly we may consider the performance requirements of any building material in place. In addition, we can have requirements on the same building material or element before it is installed in the building or even before we know how it will be used.

Then we want to quantify the requirements, i.e. usually to express them in figures. The corresponding properties must be determined so that possible alternatives can be compared. Otherwise quantitative performance requirements are meaningless. The comparison is based on calculation methods or performance test methods, where the affecting factors are given by the future situation or use of the building material or element. We must use the same factors and methods over the whole comparison field. It should be possible to control the results on an unused object and later on in the building.

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[2] Figures in brackets indicate the literature references at the end of this paper.

Performance requirements may be expressed quantitatively in terms of quality classes. I use in this paper 5 classes, marked 0, 1, 2, 3 and 4. If class 0 is allowed, it usually means no requirements, whereas class 4 usually is the highest class. Similar classifications have been used by other authors, e.g. by UEAtc (3). However, it is possible that formally lower classes in certain respects are considered to have a higher quality than classes with a high figure. An example is given in 3.2.(a).In such cases it is possible that a certain class exactly is requested, neither higher nor lower, or a certain class as a maximum.

Present discussions about advantages and disadvantages of different contract methods seem to agree with the fact that a performance type of total contract should be tried in practice. A tender should be given for a building program where the requirements for the building are fixed but the details are open.It would then be possible for the contractor to use the technique and the suppliers that result in the cheapest and best way to fulfil the requirements. As long as we do not have the necessary performance requirements, it is impossible to use complete performance specifications. However, when such requirements are obtained, they could be used for any form of building contract.

Several published performance analyses about floors contain lists of properties and factors of interest, e.g. Sneck, Bring, Lossius, Malmstedt, Nielsen and Schjödt (1). A number of these properties have been studied more closely. Bring (4) has published test methods which allow comparison between different flooring materials and flooring constructions. Later on Bring (2) suggested performance requirements for 17 properties. It is possible to use these requirements in building programs or specifications. The suggestions are based on results obtained in laboratory tests and field observations. This paper is an extract of the last mentioned report.

Whether the properties are valid for different floor materials can be seen partly from the comments, partly from Table 1, where usual quality classes for certain properties have been brought together. Table 2 contains a list of residential rooms with examples of requirements. Test results are not known for all combinations of material groups and properties. Therefore, the classification of each property, the quality classes in Table 1 and the requirements in Table 2 are partly based on my own test results, partly on speculation.

Desired quality classes for certain properties of a floor can often be obtained in several different ways. However, different solutions generally have different qualities and it happens that extremely high requirements on some properties must be combined with low requirements on other properties of the same floor. Already extreme requirements on two antagonistic properties - like resistance to indentation and warmth to touch - might result in the elimination of almost all possible solutions.

It would be better to refer to building codes for requirements but this seems not to be possible today. Let us look at ISO as an example.

Standardized test methods for flooring usually concern special materials and can seldom be used for objective comparisons between different types of materials or constructions. ISO is now (1971) trying to standardize test methods for flooring. The work is done in different technical committees (TC) with different interests. Consequently we hardly can expect recommendations for methods, suitable for performance comparisons. With regard to the general agreement that seems to prevail (Birkeland (5), Blachère (6) and Wright (7)) about the advantagesof the performance approach, it ought to be possible to influence the ISO so that the work in the different TC would be coordinated and concentrated on getting a basis for comparison between different materials and constructions.

3. Properties and Requirements

3.1. Flatness

(a) Introduction

Floors must be flat enough to place furniture and provide a suitable support for the intended activities. For pedestrians and moving wheeled vehicles the floor must be flat along straight lines at the floor surface. This also applies to movable partition walls and furnishing details with continuous, straight underside. Four-leg furniture should touch the floor simultaneously with all legs and therefore the corresponding four points of the floor surface must lie near to the same plane.

(b) Requirements

Quality class	Maximum deviation from a straight edge with length				Maximum deviation for fourth leg of square furniture with sides					
	2 m(2.19 yd)		4 m(4.38 yd)		0.5 m(0.55 yd)		1 m(1.09 yd)		2 m(2.19 yd)	
	mm	in	mm	in	mm	in	mm	in	mm	in
0	>5	>0.20	>8	>0.32	>5	>0.20	>6	>0.24	>10	>0.39
1	5	0.20	8	0.32	5	0.20	6	0.24	10	0.39
2	3	0.12	5	0.20	3	0.12	4	0.16	7	0.28
3	2	0.08	3	0.12	2	0.08	3	0.12	5	0.20
4	1	0.04	2	0.08	1	0.04	2	0.08	3	0.12

(c) Test Methods

The floor can be levelled and deviations from flatness calculated. Regarding straight lines it is easier and quicker to measure the deviation of the surface from a straight edge lying on the floor. For square furniture with 0.5 m side a special measuring instrument is used. It is known as a "measuring chair", figure 1.

(d) Comments

For floors in homes, offices etc. a 2 m (2.19 yd) straight egde and a square with 0.5 m (0.55 yd) side are appropriate while a 4 m (4.38 yd) straight edge is mainly used for factory floors.

It is obviously easier to make flat floors and subfloors of wood, fibre building board and wood particle board than of concrete. In the former cases class 3 may be required, whereas class 2 so far has been normal for concrete floors. Flatness of residential floors has been discussed by Bring (8).

Deformation of buildings are common after laying floors, by settling, deflections, moisture movements, etc. Consequently the flatness of a floor may vary with time.

3.2. Surface Evenness

(a) Introduction

With regard to the appearance, hygiene (cleaning and maintenance), comfort, security, rolling resistance and durability we can have different requirements on evenness. Especially with regard to slipperiness it might happen that the rougher the floor, the better. However, even floors are usually desired.

(b) Requirements

Quality class	Maximum deviation	
	mm	in
0	>5	>0.20
1	5	0.20
2	2	0.08
3	0.5	0.02
4	0.2	0.008

(c) Test Method

Surface evenness is measured with the help of a displacement transducer which is moved along a horizontal girder, figure 2. The feeler of the measuring instrument is furnished with a little wheel which rolls on the floor. The wheel consists of a ball bearing of steel with 4 mm (0.16 in) diameter and 1.2 mm (0.05 in) width of the outer ring which serves as a tire. The recorded profile is treated by drawing a comparison line, representing an even floor surface. This is made by connecting heights, situated at least 40 mm (1.6 in) from each other, with straight lines in the way that is the most favourable for the building contractor. However, you have to draw the comparison line so that the angle-changes at the breaking points do not exceed the equivalent of 0.02 radians at the floor. The deviation of the floor profile from the comparison line indicates the size of the surface evenness.

(d) Comments

The surface evenness of thin, prefabricated flooring of linoleum, vinyl plastic, etc. is often so good that the deviations are within 0,1 mm. An embossed surface can, however, have bigger deviations, up to several mm. The surface evenness is often influenced by the properties of the sub-floor, the composition of the aggregates or the laying skill. Moreover, it must be noticed that the evenness can be changed considerably by wear.

3.3. Warmth to Touch

(a) Introduction

Whether a floor is considered as warm or cold, depends on several factors: the climate, heating system, draught, whether we are walking, standing or sitting, heat insulation of the shoe soles, air temperature, floor temperature , thermal diffusivity, etc. Insufficient warmth to touch can lead to replacement of floor, i.e. shorter life. In order to get something with which to compare, a testing method with an "artificial foot" has been developed, in which several of the above factors are constant. The foot is calibrated by comparison with human reactions.

(b) Test Method

The "artificial foot" is a cylindrical box containing water of higher temperature than that of the floor. The "foot" is placed on a thin heat-flow device lying on the floor. The amount of heat transmitted from the "foot" to the floor is measured and integrated for 1 minute and 10 minutes according to DIN 52614 (9).

(c) Requirements

Quality class	Maximum amount of heat transmitted from the "artificial foot" to the floor during			
	1 minute		10 minutes	
	kWs/m^2	Btu/sq.yd	kWs/m^2	Btu/sq.yd
0	>63	>50	>400	>317
1	63	50	400	317
2	50	40	290	230
3	38	30	190	151
4	21	17	105	83

(d) Comments

The testing method is developed considering naked feet. The classification was originally made by J.S. Cammerer and W. Schüle (10). In this paper it is somewhat extended. Concisely we can say that the results for 1 minute are of interest for persons walking, whereas the results for 10 minutes concern persons sitting.

We should be able to use a floor of class 0 in places where we normally walk and have thick footwear or where the floors have a moderately high temperature (preferably 25-27°C,77-81°F). The class 1 should give sufficient warmth to touch at about 20°C (68°F) to a sedentary person with thick footwear. At 20°C (68°F) sedentary persons with normal footwear must have class 2 and those with exceptionally thin footwear class 3. For sedentary persons with naked feet the floor ought to have class 2 at 25-27°C (77-81°F) and class 3 at 20°C (68°F). For persons walking on the floor with naked feet even class 2 ought to be accepted at 20°C (68°F) and at 25-27°C (77-81°F) class 1.

3.4. Resistance to Indentation

(a) Introduction

Indentations in floorings result in unevenness. Certain materials become compressed. Accordingly, cleaing and maintenance can become more difficult, the impact sound insulation can become worse and the appearance can deteriorate. It might be advisable to consider the appearance first of all because it influences the durability very much. However, today we have no accepted method to classify indentaions on the basis of the appearance.

(b) Requirements

Quality class	Maximum residual indentation for			
	short-term test 5 minutes after unloading		long-term test 91 days after unloading	
	mm	in	mm	in
0	>1.5	>0.059	>1.0	>0.039
1	1.5	0.059	1.0	0.039
2	0.8	0.032	0.7	0.028
3	0.3	0.012	0.4	0.016
4	0.1	0.004	0.1	0.004

(c) Test Methods

Tests are made with short-term loading and long-term loading. A steel ball of diameter 20 mm(0.8 in)is placed on the surface of the flooring and loaded.

After the load has rested a prescribed time, it is completely withdrawn and the indenting body removed. In the short-term test a load of 490 N (110 lbf) rests for 5 minutes. In the long-term test a 245 N (55 lbf)load rests for 7 days. The methods are described by Bring (4).

(d) Comments

The short-term loading is intended to correspond to pedestrians, sloping chair legs, loaded carts at rest, etc. whereas the long-term loading gives an idea about the indentations of furniture and other equipment that seldom is moved. Short-term indentations may become a problem, if the indentation recovery is not rapid. Therefore, it seems suitable to base the judgement on the residual indentation five minutes after the unloading. As heavier furniture is seldom moved, we should accept the fact that the indentations are deep immediately after unloading. The requirements refer to the indentations which remain 3 months after unloading.

3.5. Resistance to Loading with Rolling Swivel Casters

(a) Introduction

The floor can loosen, be compressed or mangled towards the sides by rolling wheels or it can be worn or crushed. This happens especially in offices, hospitals, factories, etc. Besides the damages,which must be repaired, the impact sound insulation, evenness, need of maintenance, and the appearance of the floors can be affected. We have no suitable method to measure change of appearance. The judgement is therefore based on changes of the surface profile, on the volume of abraded material and on ocular inspection.

(b) Requirements

Quality class	Depression of surface profile and volume abraded material after loading with									
	245 N (55 lbf)on a chair caster				1960 N (441 lbf)on a steel caster of a cart					
	maximum depression		mean depression		maximum depression		mean depression		abraded volume	
	mm	in	mm	in	mm	in	mm	in	cm^3	cu.in
0	>1.6	>0.063	>1.2	>0.047	>5	>0.197	>4	>0.158	>300	>18.30
1	1.6	0.063	1.2	0.047	5	0.197	4	0.158	300	18.30
2	0.9	0.035	0.6	0.024	2	0.079	1.5	0.059	100	6.10
3	0.4	0.016	0.2	0.008	0.5	0.020	0.2	0.008	20	1.22
4	0.1	0.004	0.05	0.002	0.1	0.004	0.05	0.002	1	0.06

(c) Test Methods

A caster with a vertical swivel axis is brought into contact with the surface of a representative test sample and then loaded. The caster and the platform on which the sample rests move simultaneously against each other in two right-angled directions in the horizontal plane. The movements are forward-and-back. The ratio of the frequencies lies between 3.9 and 4.1 but not exactly at 4. Depending on the type of application a test is made either with a chair caster or a caster of a cart, figure 3. Changes are measured after 10.000 drives in the faster direction. The method is described by Bring (4).

(d) Comments

A load of 245 N (55 lbf)on each caster corresponds approximately to the loading in an office where the chairs are furnished with casters. Different types of wheels,however, give different effects. Consequently, the floors can be classified in different ways with different wheels. The cylindrical wheel of thermosetting plastic, which is prescribed for the method (4)is one of those causing less damage. In the future it might be advisable to involve two or more wheelswith different effects. Floors in hospitals, factories, etc. are exposed to different loads from the relatively light load of pneumatic tires to heavy loads on steel casters. All these variations cannot be tested. The method with a rolling steel caster indicates which floors are less suitable for heavy loads on hard casters.

3.6. Colour Fastness to Light

(a) Introduction

Fading of floorings is generally most pronounced in daylight. Floorings under furniture or carpets are not affected by light. This may lead to a colour variation which can be disturbing if the furniture is moved. Uneven colour change is an important reason for replacement of floorings.

(b) Requirements

Quality class	Colour fastness according to comparison with blue wool standards
0	< 5
1	5
2	6
3	7
4	8

(c) Test Method

When testing in daylight, colours change very slowly, The xenon lamp has proved to be a reliable and quicker substitute for the sun. The colour fastness is tested by putting the samples under the artificial light of a xenon lamp and comparing the effect with the fading of a set of dyed wool standards which is put under the lamp simultaneously. The colour fastness is expressed with a figure between 1 and 8, whereby 8 is the best according to ISO/R 879 (11).

(d) Comments

The colour fastness of a flooring depends very much on the quality of the pigment. As a pigment of high quality is often expensive, many manufacturers for certain colours choose pigments with inferior colour fastness. As floorings ought to be durable, it is unsuitable to accept the use of pigments with a poor colour fastness. It is proposed that colour fastness 1-4 should, in principle, be considered as unacceptable. Class 0 should be accepted only for premises practically without light, or for floors whose appearance is of no importance. For rooms with north windows only and rooms with usual electric light but no daylight class 1 could be accepted. The normal class is number 2 but for rooms where the floorings often are sunlit we should chose class 3.

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Table 1. Typical quality classes for different properties of floors and subfloors. The table is based on results on actual floors and laboratory tests.

i = irrelevant to the material
u = classification depends on the subfloor quality
- = test method not valid for the material

Group of materials	Flatness	Surface evenness	Warmth to touch	Resistance to indentation	Resistance to loading with rolling swiwel casters		
					chair casters	steel caster of a cart	
					depression	depression	abraded volume
Concrete	3-2	3-1	1-0	4-3	4-3	2-0	2-0
Terrazzo	3	4-3	1-0	4	4	2-0	2-0
Plywood, chipboard, fibre building board	3	4	2	3-2	4-2	i	i
Metal tiles and grating	3	3-1	1-0	4	4	4-3	4
Natural stones	3	3-1	1-0	4	4-3	3-0	3-0
Ceramic tiles	3-2	3-1	1-0	4	4	3-2	4-2
Compressed asphalt tiles	3	3-2	1-0	3	3	3-2	4
Mosaic tiles (glass, ceramic)	3-2	3-2	1-0	4	4	i	i
Wood (blocks, boards, etc.)	3	3	3-2	3-2	3-2	3-2	4
End grain wood blocks	2	2	3	3	4	3	4
Carpets	u	4-2	4-3	-	1-0	i	i
Cork tiles	u	4-3	3-2	2	3	i	i
Decorative asphalt tiles	u	4-3	1-0	3-2	3-2	i	i
Linoleum	u	4	2-1	3	3-2	i	i
Printed linoleum and feltbase	u	4-3	2-1	3-2	3-2	i	i
Rubber	u	4-3	2-1	3	3	i	i
Vinyl plastic	u	4-3	3-0	3-1	3-1	3-1	4-3
Magnesium oxychloride	2	3-2	2-0	4-3	4-3	2-0	2-0
Asphalt emulsion	2	3-2	2-1	1-0	2-0	1	4-3
Mastic asphalt, asphalt concrete	2	3-1	2-0	1-0	2-0	3-1	4
Thermosetting resins (epoxy, polyurethane, polyester, etc.)	u(3-2)	4-2	1-0	4-2	4-3	4-1	4-2
Floor seals	u	u	u	u	4-3	4-3	4

Table 2. Examples of performance requirements for residential floors. The examples are mainly based on today's standard in Scandinavia. For some properties the variation range is influenced by the subfloors - normally concrete or wood products. For other properties it is more influenced by the floorings e.g. in the choice between ceramic tiles and vinyl sheet for a bathroom. See also table 1.

Property	Residential room and quality class										
	Living room	Bedroom	Nursery	Hobby-room	Kitchen	Dining room	Washing room	Bathroom	WC	Entrance	Hall
Flatness	3-2	2	2	3-2	3-2	3-2	3-2	3-2	2	2	2
Surface evenness	4-3	3	3	4-2	4-3	4-3	4-3	4-3	3	3-2	3
Slopes	2	2	2	2	2	2	3	3	1	2	2
Warmth to touch	4-2	3	3	3-1	3-2	3-2	3-1	3-1	3-1	1-0	2-0
Resistance to indentation	4-2	3-1	3-1	4-1	3-1	3-1	4-2	4-2	3-1	4-2	4-1
Colour fastness to light	3-2	3-1	3-1	3-1	3-1	3-1	3-1	3-1	2-1	3-1	2-1

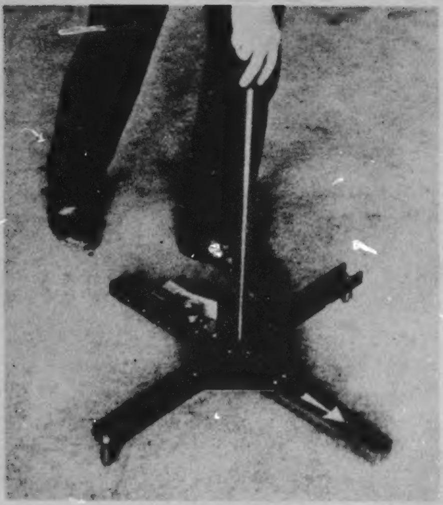
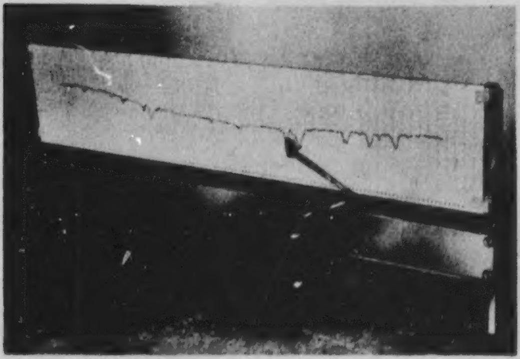


Fig. 1. "Measuring chair" for measuring flatness of floors with reference to square furniture with 0.5 m(0.55 yd) side. The crossing arms form diagonals in the square. At the ends of the arms there are three fixed legs, the fourth being vertically adjustable. This is connected with a dial from which the deviation of the floor from the plane can be directly read off.

Fig. 2. Device for measuring profiles of floor surfaces. A mechanical displacement transducer is moved along a straight bar tracing the floor surface. It is driven by a crank at the back side. A profile is drawn with ten-fold vertical magnification.



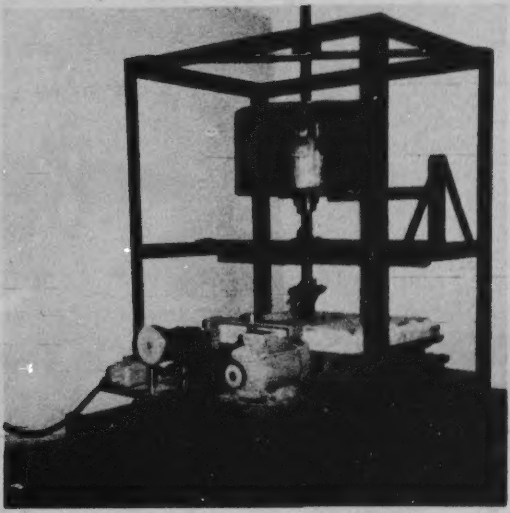


Fig. 3. Apparatus for loading with a rolling swivel caster from a cart. The loaded wheel can be rotated horizontally. The floor is simultaneously movable in two directions at right angles to each other. In a test the wheel rolls on the specimen following a path similar to a Lissajou pattern which is successively changed.

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Performance Analysis of Floors

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The paper discusses the main principles, which may be used in setting up performance requirements for floors. Performance requirements, which define the performance of a floor may be derived from an analysis of the external factors, which affect a floor in use by juxtaposition of the external factors and the properties of the floor. The following levels of building are considered in the analysis: space, building element, product combination, product, material. The analysis of external and internal factors as well as the relation between external and internal factors has been carried out on these levels. An evaluation technique, which could be used for selection and development of floors and floorings has been developed. The method is based on the identification and classification of the external factors, classification of rooms, listing of requirements and classification of rooms according to the requirements. The main purpose of the paper is to give an example of how the ideas of performance analysis could be applied to floors.

La communication discute les principes généraux qui peuvent être utilisés pour fixer les exigences de performance pour les sols et planchers. Les exigences de performance qui définissent la performance d'un sol peuvent être déduites d'une analyse des facteurs externes qui affectent l'usage d'un sol, en juxtaposant les facteurs externes et les propriétés d'un sol. Les niveaux de construction suivants sont pris en considération dans l'analyse: espace, élément de construction, combinaison de produits, produit, matériau. L'analyse des facteurs externes et internes de même que le rapport entre les facteurs externes et internes a été complétée à ces niveaux. Une technique d'évaluation qui pourrait être utilisée pour la sélection et la réalisation de sols et de revêtements de sols a été développée. La méthode est fondée sur l'identification et la classification des facteurs externes, la classification des pièces, le catalogue des exigences et la classification des pièces en fonction des exigences. Le but principal de la communication est de donner un exemple de la manière dont les idées de performance peuvent être appliquées aux sols et planchers.

Key words: Classification of floors; evaluation of floors; external factors; floorings; floors; performance analysis; properties of floors.

1. Introduction

Performance requirements of floors may be derived from an analysis of the external factors affecting a floor in use. The selection of floors can be based on the comparison of the performance requirements of floors and the properties of different kinds of floors. The performance requirements also give guidelines for the development of new types of floors and flooring materials.

In the discussion the external factors referred to are those which affect the floor from the outside. The internal factors are properties of the floor itself.

2. Levels of examination

The subject of building may be looked upon as a series of levels in a hierarchy from an overall consideration of the building needs of the nation to the detailed structure of building materials [1][1]. The building needs of the nation include all kinds of buildings, as housing, office buildings, schools, factories, etc.

Following levels are considered in the analysis of floors:

space
building element
part of building element
product combination
product
material

The higher levels (Space, building element) are decisive for the requirements which the floor has to fulfill in practice. On the lower levels detailed information related to the properties of products is required.

Space (Room). The use of the room and the activities performed in it determine both qualitatively and quantitatively the environmental agents affecting the floor in use. Often the use of the room determines the minimum and maximum values of properties of the floor.

Building element (Floor). The intermediate floor (Fig. 1) is a horizontal space divider which consists of one or more layers. The intermediate floor consists of the floor-ceiling construction. It includes the entire element, e.g., in addition to the floor also the ceiling of the room below. In order to evaluate the performance of floorings etc., the total performance of the intermediate floor has to be considered.

Part of building element (Flooring, finish floor). In some cases this uppermost layer of the intermediate floor may function as a wearing surface, but usually the floor consists of a subfloor, which is laid upon the structural floor and covered with a flooring. Therefore, the interaction between the structural floor, subfloor and the flooring must be considered.

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[1] Figures in brackets indicate the literature references at end of this paper.

Product combination (Different layers of floor construction). The compatibility of various products is considered, for instance, the interaction of flooring and adhesive.

Product (Flooring). The uppermost layer - usually a flooring - mainly functions as a wearing surface, and the final decisions on flooring requirements are determined here.

Material (Flooring material). The evaluation of the performance of a flooring may very often be dependent on the material (substance) the flooring is made of.

3. Analysis of the floor

In order to evaluate the performance of a floor the factors which set requirements on floors should be clarified. These external factors may be divided into [1]:

1. Human goals
   - non-technical
   - technical
2. Environmental factors and agents
3. Economic
4. Legislative

The analysis of floors is an example on the ideas and techniques involved in the performance analysis described in [1].

On the level, "room" (Table 1) the analysis consists of listing the human goals, which may be set on floors on this level. These are the initial needs, values and goals that are important for the user.

The second stage of the analysis has been carried out on the building element level "intermediate floor" (Table 2). The factors which may influence a floor have been listed. The external factors consist of the human goals (physiological, anthropometric, psychological, sociological), derived on the level, "room"; environmental factors and agents; and economic and legislative factors. The analysis of external factors must be carried out on various stages of building (manufacture, storage, transport, construction, etc.). The properties of the floor - the internal factors - which are of interest in order to relate the external and internal factors have also been tentatively listed.

The lists of external and internal factors on the product level, "flooring" are in Table 3. The external factors are essentially the same as on the level, "intermediate floor".

As the analysis is a only draft indicating the principles, the lists are not complete. The analysis shows that the "language" spoken at different levels may vary as can be seen in the list of properties. The slipperiness of the "floor" is equivalent with the coefficient of friction on the level, "flooring".

Many properties are the same on different levels. This may indicate a lack of knowledge as we do not know what properties of a product would really match the requirements put on a higher level. It is often very difficult to translate a "non-technical" human goal into a "technical" material property. In this connection it may be possible to discuss subjective and objective requirements [2]. In Tables 1 and 2 the corresponding properties are marked with the same number. The transformation of language can thus be followed from one level to the other.

In Tables 2 and 3 the relations between external and internal factors are shown. This kind of performance analysis technique gives the relevant attributes of the floor as well as the reason why these attributes are required.

4. Evaluation

Numerous methods have been developed for the evaluation of the effects of environmental agents as well as for the measurement of many physical properties. The correlation between service conditions and the tests is a problem. Wear testing is a good example. At present there are no methods which give exact information on the behaviour of floors in practice. In fact, different service conditions ought to be simulated by different wear tests in the laboratory [3].

The lack of evaluation techniques for factors related to human goals is quite evident. The interaction of human goals and technical properties ought to be studied more intensively. Evaluation techniques for floors have been discussed for instance by Bring [4] and [5].

5. Classification of floors

A systematic procedure for selection and development of floors and floorings may be accomplished with the aid of the performance approach. This may be based on the identification and classification of the external factors, classification of rooms, listing of requirements, and classification of rooms according to the requirements. At present the results account mainly for the environmental agents and factors and the corresponding requirements for the flooring. The UPEC system [6] can be cited as a fore-runner for the procedure which is described in [7].

The external factors have been given quantitative ratings and they have been divided into five classes (Table 4) as agreed upon in a Scandinavian flooring committee. On the basis of the quantitatively classified external factors it is possible to classify rooms as exemplified by Table 5. The performance requirements may be quantitatively classified according to the same principles (Table 6). Requirements have been classified for instance by Bring [8].

6. Conclusions

The basic principles of a performance analysis technique for floors have been discussed. The main purpose of the paper is to give an example of how the ideas of performance analysis could be applied to floors. The tables should be regarded as examples on the performance analysis procedure. The general principles for this kind of analysis have been published earlier [9].

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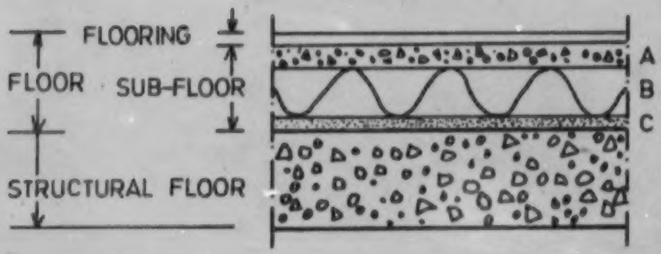

Fig. 1. Intermediate floor. The figure defines the terminology of the paper. In the example, A = screed, B = thermal insulation and C = damp-proof membrane.

Table 1. Analysis of floors on the level, "room".

External factors

1. Human goals
   - physiological
   - anthropometrical
   - psychological
   - sosiological

   Examples:

   - Ease of walking
   - Ease of furnishing
   - Safety from falling
   - Structural safety from falling through the floor
   - Suitability for play (children)
   - Attractive appearance
   - Cleanability or maintenance
   - Replaceability
   - Durability
   - Value
   - Comfort
   - Hygiene
2. Environmental factors and agents (see Table 2)
3. Economic
   - Initial costs
   - Costs of maintenance
   - Costs of repair
   - Costs of replacement
4. Legislative
   - Building codes
   - Health and safety regulations, etc.

Table 2. Analysis of floors at the level "intermediate floor"

Property External factor	1 Slipperiness	2 Evenness	3 Planeness	4 Deformations (flexibility)	5 Hardness Softness	6 Surface area	7 Structural strength and stability	8 Warmth	9 Liability to get dirty	10 Cleanability	11 Colour	12 Texture	13 Reflection of light	14 Replaceability	15 Durability	16 Resistance to indendation	17 Resistance to impact loads	18 Resistance to wear	19 Water tightness	20 Resistance to water	21 Heat insulation	22 Resistance to heat	23 Resistance to fire	24 Resistance to cigarrettes	25 Electric resistance	26 Static electricity	27 Sound insulation	28 Insulation against radiation	29 Resistance to radiation	30 Resistance to light	31 Reflection of light	32 Resistance to chemicals	33 Resistance to micro-organisms	34 Emission of odour, dust, gases	35 Price
1. Human goals																																			
Ease of walking	x	x	x	x	x																														
Ease of furnishing		x	x			x																													
Safety from falling	x	x	x																																
Structural safety from falling through the floor							x																												
Suitability for play								x	x	x																									
Attractive appearance									x	x	x	x	x																						
Cleanability or maintenance									x	x																									
Replaceability														x																					
Durability																																			
Value																																			
Comfort								x																											
Hygiene																																		x	
2. Environmental factors and agents																																			
Design loads (Structural)							x																												
Concentrated loads															x	x																			
Rolling loads																x																			
Impact loads																	x																		
Wear																		x																	
Water and moisture																			x	x															
Heat																					x	x													
Fire																							x												
Cigarrettes																								x											
Electricity																									x	x									
Structureborne sound																											x								
Airborne sound																											x								
Radiation																												x	x						
Light												x																		x	x				
Chemicals											x																					x			
Dirt									x		x																								
Micro-organisms																																	x		
3. Economic																																			
Initial costs																																			x
Costs of maintenance		x				x			x	x					x																				
Costs of repair															x																				
Costs of replacement																																			
4. Legislative																																			
Building codes																																			
Health and safety regulations																																			
etc.																																			

Table 3. Analysis of floors at the level "flooring"

Property / External factor	1 Coefficient of friction	2 Evenness	3 Planeness	4 Deformations (flexibility)	5 Hardness Softness	7 Strength of materials	8 Thermal conductivity	8 Temperature	9 Liability to get dirty	10 Cleanability	11 Colour	12 Texture	13 Light reflectivity	14 Replaceability	15 Durability	16 Resistance to indentation	17 Resistance to impact loads	18 Resistance to wear	19 Water permeability	20 Resistance to water	21 Thermal conductivity	22 Resistance to heat	23 Ease of ignition	23 Flame spread	23 Smoke generation	24 Resistance to cigarettes	25 Electric resistance	26 Static electricity	27 Sound absorption	27 Weight of material	28 Insulation against radiation	29 Resistance to radiation	30 Resistance to light	31 Light Relactivity	32 Resistance to chemicals	33 Resistance to micro-organisms	34 Emission of odour, dust, gases	35 Price
1. Human goals																																					
Ease of walking	x	x	x	x	x																																
Ease of furnishing		x	x													x																					
Safety from falling	x	x	x																																		
Structural safety from falling through the floor						x																															
Suitability for play							x	x		x																											
Attractive appearance									x	x	x	x	x																								
Cleanability of maintenance									x	x																											
Replaceability														x																							
Durability																																					
Value																																					
Comfort							x	x																												x	
Hygiene																																					
2. Environmental factors and agents																																					
Design loads						x																															
Concentrated loads																x																					
Rolling loads																x																					
Impact loads																	x																				
Wear																		x																			
Water and moisture																			x	x																	
Heat							x														x	x															
Fire																							x	x	x												
Cigarettes																										x											
Electricity																											x	x									
Structureborne sound																													x	x							
Airborne sound																														x							
Radiation																															x	x					
Light																																	x	x			
Chemicals										x																									x		
Dirt									x	x																											
Micro-organisms																																				x	
3. Economic																																					
Initial costs																																					x
Costs of maintenance		x							x	x					x																						
Costs of repair															x																						
Costs of replacement																																					
4. Legislative Building codes, Health and safety regulations, etc.																																					

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Table 4. Classification of external factors (environmental factors and agents).

Factor	0	1	2	3	4
Uniform live load kN/m^2 (lb/sq. ft)	≦ 1.5 (30)	≦ 2.0 (40)	≦ 3.0 (60)	≦ 4.0 (80)	>4.0 (80)
Point load kN (lbf)	≦ 1.5 (340)	≦ 3.0 (675)	≦ 10 (2250)	≦ 20 (4500)	>20 (4500)
Concentrated load N/cm^2 (lb/sq. in)	≦ 10 (14.5)	≦ 100 (145)	≦ 500 (725)	≦ 2000(2900)	>2000 (2900)
Rolling load N/cm^2 (lb/sq. in)	≦ 10 (14.5)	≦ 100 (145)	≦ 500 (725)	≦ 2000 (2900)	>2000 (2900)
Wear by foot traffic	Light	Moderate	Severe	Very severe	Extreme
Water	No water	Cleaning with damp cloth or immediate drying	Water is no longer than 12 h on the floor	Continuously	Continously under water
Chemicals	No chemicals	Removed immediately	No longer than 12 h on the floor	The effect of the chemical is not continuous	Continuously under effect of the chemical
Gases ppm	= 10	10...100	100...10000	10 000...100000	100 000
Light					
UV					
Radioactive					
Temperature °C (°F)	+15...25 (60...75)	+25...50 +15...0 (75...120) (60...32)	+50...100 0...-15 (120...210) (32...5)	+100...1000 -15...-30 (210...1800) (5...-20)	+1000 -30 (1800) (-20)
Cigarrettes					
Dirt					
Maintenance (Cleaning)	Dry cleaning	Dam cleaning with soap	Cleaning with natural cleaning materials	Cleaning with strong cleaning materials	Cleaning with scouring powder and strong cleaning materials
Airborne sound dB	40	40...50	50...70	70...90	>90
Electric current					
Static electricity					

Table 5. Classification of external factors in rooms.

Residential rooms External factor	Living room, dining room, hall, room with opening into living room	Bedroom and lobby	Kitchen, service room	Laundry	Bathroom	WC	Staircase
Uniform load	1	1	1	1	2	1	3
Point load	2	2	2	2	2	2	2
Concentrated load	3...4	3...4	3	2	2	2	3...4
Rolling load	2	1	2	2	2	-	-
Wear of foot traffic	2...3	2	3	2	2	1	4
Wear other than foot traffic	2	2...3	2	3	2	2	2
Water	1...3	1...3	3	4	3...4	3	3...4
Chemicals	1	1	2...3	4	2	1	
Gases							
Light							
UV							
Radioactive radiation							
Heat							
Temperature	1	1	2	2	2	1	2
Thermal shock	2	1	2	2	2	1	
Cigarrettes	2...3	2	2				4
Dirt							3...4
Maintenance	1...3	1...3	4	4	4	3	4
Airbone sound	3	2...3	3...4	3...4	2	2	3...4
Impact sound							
Electric current							
Static electricity							

Table 6. Classification of requirements on floors, examples

Property	0	1	2	3	4
	Very low or no requirements	Low	Normal	High	Very high
Loadbearing capacity kN /m^2 (lb/sq. ft)	≦1,5 (30)	≦2,0 (40)	≦3,0 (60)	≦4,0 (80)	>4,0 (80)
Resistance to short-time indentation, max. remaining indentation ([4], method 21) mm (in.)	>1.5 (0.06)	0.8...1.5 (0.03...0.06)	0.3...0.8 (0.012...0.06)	0.1...0.3 (0.004...0.012)	<0.1 (0.004)
Resistance to long-time indentation, max. remaining indentation ([4], method 22) mm (in.)	>1.0 (0.04)	0.7...1.0 (0.03...0.04)	0.4..0.7 (0.015...0.03)	0.1...0.4 (0.004...0.015)	<0.1 (0.004)
Resistance to rolling loads, max. depression ([4], method 24) mm (in.)	>1.6 (0.06)	0.9...1.6 (0.035...0.06)	0.4..0.8 (0.015...0.035)	0.1...0.3 (0.004...0.015)	<0.1 (0.004)
Resistance to rolling loads, max. depression ([4], method 25) mm (in.)	>5 (0.2)	2...5 (0.09...0.2)	0.5...2 (0.02...0.09)	0.1...0.5 (0.001...0.02)	<0.1 (0.004)
Resistance to wear					
Resistance to water and chemicals					
Resistance to gases					
Resistance to burning cigarrettes					
Resistance to extinguishing of cigarrettes					
Liability to get dirty					
Maintainability					
Airborne sound insulation intermediate dB	45	45...49	49...53	53...55	>55
Impact sound insulation dB	75	75...70	67...65	65...63	<63
Electric resistance [4]					
Hardness of surface					
Planeness of surface					
Inclineness of surface					
Cracks					
Width of joints					
Slipperiness					

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Strength Criteria of Glued-Laminated Timber

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Accurate knowledge of the properties of any engineering material is essential to its proper uses. Recognizing this fact, the U.S. Forest Products Laboratory has had a continuing research program to better define the strength characteristics of glued-laminated construction, a versatile engineering material. Early research in the 1930's was the foundation for the glued-laminated industry in the United States. Design and manufacturing criteria were developed based on glued members which were relatively small by today's standards. With industry growth, manufacturing techniques and architectural design developed to the extent that timbers of almost unlimited size and shape were possible, but engineering technology did not keep pace. However, an extensive research effort during the 1960's has developed related engineering technology for the large timbers. This research established the effect of several factors involving strength and design of large timbers--a principal one being the effect of tension lamination quality on beam strength. Such research has resulted in revised specifications for glued-laminated timbers which will insure a more reliable engineering material.

Une connaissance exacte des propriétés de tout matériau de génie civil est essentielle pour une application appropriée. Reconnaissant le fait, le Laboratoire des Produits Forestiers des Etats-Unis a poursuivi un programme de recherches continues pour mieux définir les caractéristiques de résistance de la construction en bois contrecollé, matériau de génie civil aux applications multiples. Une recherche faite dès les années 30 a lancé l'industrie du contrecollage aux Etats-Unis. Des critères d'étude et de fabrication furent développés à partir d'éléments collés relativement petits comparés à ceux d'aujourd'hui. Avec l'expansion de l'industrie, les techniques de fabrication et les études architecturales se développèrent au point que des charpentes de grandeur et de forme presque illimitées furent possibles. Cette expansion prit place sans des progrès parallèles dans la technologie du génie civil. Toutefois, une technologie apparentée pour les grandes charpentes se développa grâce à un vaste effort de recherches durant les années 60. Ces recherches ont défini les effets de plusieurs facteurs affectant la résistance et la conception des grandes charpentes, le principal étant l'effet de la qualité de tension du contrecollage sur la résistance des poutres. De telles études ont abouti à des spécifications révisées pour les charpentes en bois contrecollé qui assureront un matériau de génie civil plus fiable.

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[1] Engineer

Key words: Defective material; design criteria; design stresses; glued-laminated timber; knots; lamination; lumber grades; prestressed wood; slope of grain; strength criteria; strength ratio; strength-reducing characteristics; structural.

1. Introduction

Glued-laminated timber is structural timber glued up from smaller pieces of wood, either in straight or curved form with the grain of all the laminations essentially parallel to the length of the member. In such a manufactured structural timber, small pieces of lumber can be positioned in the member in accordance with their strength, as affected by knots and other strength-reducing characteristics, and in accordance with the strength requirements of the element. Such efficient use of high and low quality, narrow width, and short length pieces of wood to manufacture high performance structural elements extends the applicability of wood as a construction material and is increasingly adaptable to our future timber economy. The continuing research to better define the characteristics of glued-laminated timber is a part of the overall objective to improve the utilization of our timber resources.

The engineering characteristics of glued structural wood members are controlled by a number of factors. These include such things as the clear wood strength, variability, period of loading, factor of safety, size of member, and strength-reducing characteristics--the principal ones being knots and cross grain. The manufacturing techniques involved in face gluing and end jointing the laminations also affect the strength of the finished product. These are governed, however, by recommended manufacturing procedures.

The effect of most of the factors controlling strength have been adequately defined for solid-sawn one-piece members and many of these same effects apply equally well to laminated timbers. However, one effect, that of knots, is considered differently in the development of stresses for glued-laminated timber as compared to the development of stresses for solid-sawn one-piece members.

This paper covers the progression in the development of glued-laminated stresses as they are controlled by knots. General cross grain is an equally important factor in affecting strength, but it can be limited so that its effect is less than that of knots. Thus knots, along with localized grain deviations associated with knots, are the primary strength-reducing factors that control the strength of glued-laminated timbers.

2. History of Glued-Laminated Construction

Glued-laminated construction originated in Germany early in the 1900's and spread throughout Europe in a relatively short time. The probable reason for its success was the scarcity of timbers of suitable size for framed construction. The good service record of glued-laminated construction in Europe provided useful data as to the permanence of glued-laminated construction. However, their test data did not apply to the United States conditions and species of wood. Also, most of the European test data were related to straight glued-laminated timbers. Thus research was started at the U.S. Forest Products Laboratory in the early 1930's to develop manufacturing techniques, design stresses, and design criteria for structural glued-laminated timbers [1].[2] Much of this work was done on curved members but the resulting information applies equally well to straight members.

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[2] Figures in brackets indicate the literature references at the end of this paper.

3. Early Research

The European experience with glued-laminated construction was a useful guide but provided only incomplete information about the characteristics of the material and other factors that may have important effects on its strength. Research at the Forest Products Laboratory was started to develop information necessary to insure the reliability of glued-laminated construction as an engineering material. One objective was to study the extent to which material with knots and other defects could be used.

Early research was based on the hypothesis that the strength of glued-laminated timbers could be controlled by selective placement of grades of material in the members. The lower grade materials could be used in the less highly stressed areas without adversely affecting the structural integrity of the member. Initial research was done on members made of material free of defects. Subsequently, the effects of defects were studied by combining clear boards with what were defined as defective boards in the midsection of the member. Clear boards were used for the outer top and bottom laminations in the completed member. The defective material was typical of No. 2 Common boards which at that time (early 1930's) permitted knots to occupy up to approximately one-half of the cross section.

Significant findings from this early research showed that using 60 percent of defective material in the midsection of the laminated member did not significantly reduce the strength below that of members consisting entirely of clear laminations. Further research indicated that the outer top and bottom 20 percent of the laminations did not need to be 100 percent free of defects to provide a member having a 100 percent strength ratio. Ultimately research established the conclusion that if the outer top and bottom 20 percent of the laminations in the member contained knots whose size was less than one-eighth of the width of the lamina, the completed member could still be designed for a strength value equivalent to that of a member with all laminations free of defects. The middle 60 percent was defective material as previously discussed. Furthermore, for a construction in which the top and bottom 20 percent of the laminations contained knots whose size did not exceed one-fourth the width of the piece, the completed member could be designed for a stress equal to 87-1/2 percent of that used for a member with laminations free of defects.

Additional material requirements specified that the laminations in the outer top and bottom 20 percent of the member could not contain any part of the pith of the tree. Also, it was suggested that all laminations should be free of knots that would be visible when the member is in place in the structure. This last requirement essentially means no knots in the top and bottom face laminations and no edge knots in all laminations.

4. Strength Ratio Concept

Having only two strength grades of glued-laminated members was somewhat restrictive. Thus, in the early 1940's a different criterion was proposed for assigning stresses to such elements. This was based on an accepted strength ratio concept that was used for solid-sawn one-piece members. This strength ratio is the ratio of the timber's strength to what it would have if no strength-reducing characteristics were present. For example, a timber with a strength ratio of 75 percent would have 75 percent of the strength of a clear piece. This definition applies equally well to a glued-laminated timber as it does to a solid-sawn one-piece member.

In the strength ratio concept, it was hypothesized that if the glued-laminated member should have 80 percent of the strength of a glued member with all defect free laminations, then the outer top and bottom laminations should have an 80 percent strength ratio. The required strength ratios for the inner laminations would be proportionally less based on their location in the member. For example, assuming a linear stress distribution in a bending member, the strength of the first inner laminations from the top and bottom faces of a 20-lamination member should be 90 percent of the strength of the outer laminations. Or if the outer laminations had a strength ratio of 80 percent, the first inner laminations should have a strength ratio of 72 percent. The limiting requirements placed on the inner laminations were that no lumber with a strength ratio lower than 25 percent could be used anywhere in the beams.

The strength ratio concept as used for solid-sawn one-piece members was apparently accepted for glued-laminated timbers without supporting data.

5. I_K/I_G Theory

During the mid-1940's procedures for making glued-laminated construction developed to the point that additional research was necessary to better define the relative strength design of such structural elements. Part of this was prompted by the great demand during World War II for heavy timbers since the supply of solid-sawn one-piece timbers was inadequate. It was believed that previous procedures for assigning stresses to glued-laminated timbers made up of different combinations of grades were overconservative. The effect of knots in a solid-sawn one-piece member was probably greater than the effect of an equivalent knot in a glued assembly due to the beneficial reinforcing effect of the adjacent plies.

The theory was still followed that a knot of a given size in a lamination will have different effects on bending strength of a glued-laminated timber depending on where the lamination is in the cross section. However, more thought was given to the combination of knot size and position relative to strength. It was hypothesized that this combined effect could be related to a physical property of the beam cross section, that of moment of inertia. Consequently, the analysis of the results of tests of beams 12 inches in depth were related to the moment of inertia of the cross section occupied by knots [2]. The beam strength was related to a nondimensional factor commonly called I_K/I_G, where I_K is the moment of inertia of the area occupied by knots within 6 inches of either side of the critical cross section and I_G is the gross moment of inertia of the beam. Thus, if the sizes and locations of knots in a laminated beam are known, the strength ratio or proportion of strength remaining can be calculated from this relationship.

Obviously, it is impractical to design a glued-laminated member if its strength is not known until the boards to make it have been assembled and the knots positioned and measured. It is equally impractical to selectively place knots of given sizes in the critical locations in the member. A method was needed to estimate the strength of a random assembly of grades of laminations. Since a random assembly was involved, the use of a statistical method was indicated. Accordingly, such a statistical approach was developed [3]. From knot size data gathered on commercial lumber grades, it was possible to develop the distribution of the knot sizes in each grade of lumber. With these distributions and using statistical procedures, it is possible to predict the value of the moment of inertia of areas occupied by knots in any 1 foot of length for any grade combination and numbers of laminations going into a glued assembly. After a level of probability suitable for use in design was chosen, the I_K/I_G strength relationship mentioned above could be used to obtain the strength ratio of the completed assembly. Such procedures were adopted for use in assigning stresses to glued-laminated timbers early in the 1950's.

6. Subsequent Research

With wood-laminating industry growth, manufacturing techniques and the architectural design developed to the extent that timbers of almost unlimited size and shape were possible. This growth resulted without accompanying advancement in the engineering technology. Since most of the design and manufacturing criteria were developed for glued-laminated timbers which were relatively small by today's standards, it was imperative that additional research be directed at strength properties of very large glued-laminated timbers. One area of this research naturally concentrated on the effect of knots on bending strength of these large timbers.

6.1 Prestressed Beam Research

During the early 1960's it became increasingly apparent that the tensile strength of structural lumber containing strength-reducing characteristics could be less than that previously assumed. In 1961 glued-laminated timbers were prestressed using the same principles as used to prestress concrete beams [4]. Such a prestressing concept is based on the hypothesis that the tensile strength of a given bending member is less than the compressive strength. While this hypothesis was contradictory to existing strength concepts for wood members, the research verified that--for a given quality of structural timber--the tensile strength was less than that of the compressive strength. By reinforcing the tensile area of a beam, the average bending strength was increased by 30 percent. The important inferences from these findings were that the tensile strength of the outer tension laminations of a glued-laminated timber may have a significant effect on the bending strength of the timber.

Following the same reasoning a small part of the research of prestressed wood beams was directed toward evaluating the importance of the tension lamination. The addition of a clear straight-grained tension lamination had a pronounced effect on the modulus of rupture of laminated beams made of L-3 grade Douglas-fir lumber. The addition of one 1-1/2-inch-thick clear lamination representing 14 percent of the beam depth increased the modulus of rupture 32 percent and one 9/16-inch-thick clear lamination representing only 5 percent of the beam depth increased the modulus of rupture 23 percent. These data indicated a potential for significant improvement in flexural strength of structural laminated beams by giving special attention to a small portion of the beam, the outer few tension laminations.

6.2 Flexural Behavior of Large Glued-Laminated Beams

A study related to size effect of large timbers afforded the opportunity to reevaluate the I_K/I_G relationship as developed in 1947 which relates bending strength to knot distribution in a beam [5]. Three beams, 31-1/2 inches deep, 9 inches wide, and 50 feet long, containing strength-reducing characteristics as could be found in commercially produced laminated beams, were evaluated. These limited data were not conclusive but they did indicate the need for further research to obtain a better understanding of the effect of knots on the bending strength of large glued-laminated timbers.

6.3 Large Beam Tests

Based on observed test failures and strength data on a few large beam tests and other related data, including tensile strength of structural lumber, the laminating industry concluded that more emphasis should be placed on the grade of the tension laminations for large glued-laminated bending members. With the available data on tensile strength of structural lumber, the American Institute of Timber Construction developed and published specifications for tension laminations in 1967. This tension lamination grade, AITC-301, was not necessarily clear and straight grained, but it was a high quality structural grade. Specific strength-reducing characteristics considered in the new grade were growth rate requirements, sizes of knots, and general and localized slope of grain. The most significant improvement in the specifications for the tension lamination grade over specifications for other structural grades was the limitations placed on localized grain deviations, separately or in combinations with knots. This had not been considered previously in grading of structural lumber.

To learn the effect of the tension lamination grade on the strength of bending members, the Forest Products Laboratory and the American Institute of Timber Construction cooperated in a research project [6]. During 1968, 26 large beams were evaluated; 16 of these beams had the tension laminations which were graded according to the AITC 301-67 requirements. An additional 10 beams had tension laminations having more restrictive requirements than those for the AITC-301 grade. A comparison of the grades is given in Table 1. Two tension lamination grades were included in this study to obtain a better understanding of the effect of the tension lamination grade on the bending strength. The tension laminations were specially selected, but all other laminations were positioned within the beams in accordance with industry practice and required grade combinations as had been determined previously by the I_K/I_G concept.

This study indicated that beams with the AITC-301 grade tension lamination probably were not adequate for the highest stress grade beams now produced by the laminating industry. The data further indicated that some of the features of the more restrictive grade (301+) were more than adequate for the highest bending stress grade laminated beams being manufactured. Results of this study also provided additional information on the requirements needed for tension laminations. Growth characteristics of tension laminations such as grain deviation in board thickness, edge knots, two knots in near proximity of each other, and regions of lightweight material were found to result in low strength beams. Particularly, finger joints in this lightweight material appeared to influence beam failure.

Based on the test results of 26 large beams, and a subsequent study of end joint strength as affected by lightweight coarse-grained wood [7], a new grade of tension lamination was tentatively proposed by AITC. A comparison of this grade, called 301A-69, and those previously discussed is shown in Table 1. Significant changes in the grade requirements were made in reference to specific gravity and to regions of lightweight coarse-grained wood.

The cooperative research program between the Laboratory and AITC continued in 1969 with an evaluation of the bending strength of 15 beams with the 301A-69 grade tension lamination [8].

Results of all test data on large beams reinforced the hypothesis that the strength of glued-laminated beams depends upon the tension lamination quality. The data also provided guidelines for setting requirements for tension laminations for beams with different assigned bending strengths.

7. Large Beam Test Data vs. I_K/I_G Theory

Tests of large beams were made because the validity of the I_K/I_G theory had been questioned for large bending members. Thus, do these data support or refute the I_K/I_G concept?

The test beam grade combinations for the large beam tests, which define the grade and position of all laminations in a beam, were taken from existing specifications for glued-laminated timbers. These grade combinations had been developed by industry associations. The I_K/I_G theory was used in developing the grade combinations. Therefore the test beams were assembled following the I_K/I_G concept as modified by the tension lamination requirement. The added tension lamination requirements did not result in any significant change in the actual I_K/I_G ratio of the beams. However, an overall general conclusion from all large beam test data was that beams with specific quality tension laminations did have strengths which were adequate to justify the design stresses assigned. One conclusion could be that the I_K/I_G theory did with sufficient accuracy estimate the effect of knots on glued-laminated beam strength if the outer tension laminations were of a high quality structural grade.

Such a conclusion indicated the need for a reevaluation of the initial development of the I_K/I_G-strength relationship. In the initial study, beams with I_K/I_G ratios ranging from 0 to 0.45 were evaluated. However, those beams with I_K/I_G ratios less than 0.266 had tension laminations that were essentially clear. This re-evaluation and the large beam data both support the concept that a selective grade requirement for tension laminations was indirectly a part of the I_K/I_G theory, at least for the higher strength beams. The combined I_K/I_G theory with the added tension grade requirement should result in reliable design criteria for glued-laminated beams.

The currently published grade combinations for beams in the 2,200 to 2,600 p.s.i. design stress classes have I_K/I_G ratios of approximately 0.25 or less [9]. As previously noted, beams with such I_K/I_G ratios that were used in the development of the I_K/I_G theory had essentially clear tension laminations. The current specifications for such beams also have the requirement for a relatively high quality tension lamination. Thus, the possible original intent of I_K/I_G theory is being more nearly followed in current specifications for glued-laminated timbers.

8. Summary

The strength of glued-laminated timbers is engineered by the selective location of strength-reducing characteristics within the member cross section. Lower grades of material can be used in the less highly stressed areas without adversely affecting the structural adequacy of the glued assembly. One of the principal strength-reducing characteristics is knots along with the localized grain deviation associated with knots. The effect of knots on the strength of glued-laminated timbers has been the objective of extensive research at the Forest Products Laboratory since the early 1930's.

The most widely accepted knot-strength relationship was developed in the late 1940's. The combined effect of knot size and location within a beam cross section was related to a physical property of the beam, that of moment of inertia. Beam strength was related to a nondimension factor commonly called I_K/I_G, a ratio of the moment of inertia occupied by knots and the gross moment of inertia of a beam.

Tests on large beams and related research since 1960 have shown that the strength of glued-laminated timbers is more reliably determined if the I_K/I_G-strength relationship is modified to include somewhat restrictive requirements on the quality of the tension lamination. The need for this modification was further verified in a re-evaluation of the initial data used in the development of the I_K/I_G concept.

Research since 1960 has resulted in revised specifications for glued-laminated timbers which will insure a more reliable engineering material.

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Table 1. Comparison of tension lamination grades

Strength Characteristics	Restrictions Within Each Grade		
	AITC 301-67	301+	AITC 301A-69
Growth rate requirements	Apply to full length	Apply to full length	Apply to full length
Specific gravity	Exceptionally lightweight pieces excluded	Exceptionally lightweight pieces excluded	Near average or above
Knots	1/4 of cross section	1/5 of cross section	1/5 of cross section
General slope of grain	1 in 16	1 in 16	1 in 16
Localized slope of grain steeper than 1 in 16	1/3 of cross section	2/3 of cross section must be free of strength-reducing characteristics[1]	2/3 of cross section must be free of strength-reducing characteristics[1]
Knots and end joints	Knots must not be within 2 knot diameters of end joints	Knots must not be within 2 knot diameters of end joints	Knots must not be within 2 knot diameters of end joints
Edge knots and associated slope of grain	--	1/8 of cross section	--
Spacing of maximum strength-reducing characteristics	--	4 feet	4 feet
Wide ring pith-associated wood	--	--	1/8 of cross section

[1] Knots plus associated localized cross grain, or knots plus associated localized cross grain plus localized cross grain not associated with knots, or localized cross grain not associated with a knot may occupy up to one-third of the cross section.

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Performance Requirements for Mechanical Fasteners Used in Building

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The selection of mechanical fasteners used for joining and fastening of materials, assemblies, and components is influenced by a variety of criteria, all of which are related directly to the anticipated performance of the assembled items. The mechanical fasteners need to be selected on the basis of their actual and economic availability, versatility, applicability, physical and mechanical properties, rigidity and damping capacity, compatibility, thermal properties, fire resistivity, reliability including their resistance to creep, maintenance and repair of the finished product, and feasibility of testing for performance evaluation and performance predictability. These performance criteria are given detailed consideration in order to facilitate the writing of performance specifications covering mechanical fasteners as well as mechanical fastening in building constructions. Whereas the subject matter is approached from the overall viewpoint, reference is made to a few selected specific applications in order to draw attention to the importance of the performance concept under given conditions.

Le choix des attaches mécaniques employées dans l'assemblage et l'attachement de matériaux, assemblages, et composantes est déterminé par une variété de critères, qui ont tous rapport au performance envisagé des objets assemblés. Le choix des attaches mécaniques doit être basé sur leur disponibilité effective et économique, leurs facultés d'adaptation, leur applicabilité, leurs propriétés physiques et mécaniques, leur rigidité et capacité de amortissement, leur compatibilité, leurs propriétés thermales, leur résistance au feu, leur sûreté de fonctionnement y comprise leur résistance au glissement, l' entretient et la réparation du produit ouvré, et possibilité d'épreuves pour l' évaluation et la prédiction du performance. Ces critères de performance sont étudiés pour faciliter la rédaction des spécifications de performance comprenant les attaches mécaniques aussi bien que l'attachement mécanique dans la construction des bâtiments. Bien que le sujet soit abordé d'un point de vue général, on fait mention de quelques applications choisies, pour faire remarquer l'importance du concept de performance dans des conditions données.

Key words: Bolts; building assemblies; building components; building constructions; framing wood; improved nails; mechanical fasteners; mechanical fastenings; nails; screws; staples.

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1. Introduction

The present status of performance requirements for mechanical fasteners used in building may be indicated by quoting from HUD's 1970 "Guide Criteria for the Design and Evaluation of Operation Breakthrough --- Housing Systems" (1)[2]: Buildings should perform "without failure of the elements or any structural connection thereto; ... inserts and hangers should not fail and/or damage structural elements to which they are attached; ....connections shall have a fire resistance equal to or greater than that of any member framing into them." According to these "Criteria", ceiling fasteners must support twice the service live load and five times the dead load because of the long-term loading. All other fasteners must support twice the dead load and twice the service live load. Service loads on installed systems include residual erection and installation stresses, temperature stresses, impact, and other dynamic loads. Failure is defined as a sudden locally increased curvature, major spalling, or structural collapse; inability to resist further load increase; increase in deflection of no less than the maximum allowable deflection under service load conditions occurring during any 10-min. period after application of the superimposed load without increase in the applied load.

Whereas the performance concept for buildings and its elements covers a multitude of aspects, in general, mechanical fasteners need to perform only as well as the fastened and fastening elements with the one long-term loading exception indicated above. This overall provision includes all aspects with reference to the building elements. Yet, mechanical fasteners can introduce a number of other aspects which are usually not given consideration in the performance concept for the building elements.

The successful use of mechanical fasteners is usually taken for granted in most performance specifications. The fasteners are expected to perform satisfactorily from every viewpoint, whereas the fastened element is given a critical going over in the specifications. In the light of this, the pitfalls of mechanical fastener systems, rather than their advantages, are emphasized in the following paragraphs in order to warn the unwary.

2. Selection of Mechanical Fasteners

2.1. Availability

If the required mechanical fastener is described in detail in a building specification, this fastener may be representative of only one type of a large number which could meet the specific performance requirements. Therefore, it is desirable to leave specifications open for the use of any fastener performing satisfactorily under given conditions. This stipulation is important because of the fact that the local trade is usually not in a position to stock all the mechanical fasteners available. This is especially the case in fields where a large number of fastener types and sizes exists which could perform satisfactorily.

Indeed, fasteners are often selected in the light of their immediate availability. Whereas a fastener one quarter of an inch longer than necessary, probably is more expensive than one of minimum length, the ready availability of the slightly longer fastener may result in overall in-place savings. Therefore, its use should be allowed provided the longer fastener does not introduce significant disadvantages, such as a danger of handling the fastened item with its nail points protruding, thereby providing a safety hazard.

Thus, it may be practical, in many instances, to accept a compromise in fastener selection because of availability. This is especially desirable since the number of fasteners to choose from can be large, with some of them possibly being non-stock items, that is, only manufactured on specific demand. Stock items can usually be supplied at lower cost than non-stock items, except in the instance of a specific demand for large quantities.

2.2. Versatility

In many instances it is desirable to use identical mechanical fasteners for as many applications as possible, instead of the most satisfactory fastener for each application, even if the total cost of all fasteners used might be higher. Reductions in the ordering, shipping, storage, and handling costs can make a single versatile fastener, when in place, less expensive than a number of special fasteners each of which is most suitable and most economical for a given applications.

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[2] Figures in parentheses indicate the literature references at end of this paper.

This became evident in the case of the V.P.I. Demonstration House (2), where the use of 33 different nails (fig. 1) was specified. Some of the fasteners could have been readily replaced by others among those specified and, thus, the number of fastener types and sizes could have been reduced considerably. Yet, one of the purposes of the Demonstration House was to show that there is a most suitable fastener for each assembly job.

Such a reduction in types and sizes of fasteners by the versatile use of a minimum number of fastener types and sizes (fig. 2) was accomplished for the construction of the Tech Motel (3) as a result of the use of simplified construction procedures and the replacement of several fasteners by a single fastener. Performance-type building specifications, in contrast to descriptive item-per-item specifications, should lead to such a desirable reduction in fastener selection.

2.3. Applicability

All fasteners have to be located and placed when and where they are needed. They have to be selected also on the basis of availability of the tools with which the fasteners are to be installed, be it in the prefabricator's plant or at the building site, for permanent or temporary tamper-proof use or for later dismantling under given conditions, for use in corrosion-protected or corrosive environments, etc.

Thus, a nail must provide satisfactory drivability; and a slightly different nail may be selected if it is to be driven with a hand-hammer or by an automated nailing machine. In the case of plastic-polymer coated nails and staples, these fasteners have to be driven at a fast rate to develop the frictional heat required to polymerize the coating and, thus, to provide a bond between fastener and surrounding material. Hence, machine driving at a rapid rate is a basic requirement for the satisfactory performance of these coated fasteners, and hammer-driving or repetitive impact driving are not acceptable.

If available space, a given location and/or circumstances do not allow hammer or machine driving of a nail, a fastener may have to be chosen which can be inserted without such tools, e.g., by using pop rivets or powder-driven pins or studs. If a nail, pin or stud is to be driven through and/or into hard materials, such as dense wood or steel, the fastener to be used has to be tough and may be a hardened-steel (heat-treated and tempered) nail, in order to prevent buckling during driving. In the fastening to relatively thin sheet-metal and steel members and components, the use of self-drilling non-hardened screws can result in effective and efficient fastening; whereas in the fastening to thicker steel members and components, self-drilling hardened-steel screws need to be used, which can be drilled effectively and efficiently even through ¼-in. steel.

In certain applications, where access to the far side of a member is not feasible and all handling and/or tightening of a fastener has to be accomplished from one side, the fastener may have to be driven or inserted from one side to transfer loads in single or multiple shear. The use of a single fastener for the transfer of loads in multiple shear can, of course, be considerably more economical than that of multiple fasteners in single shear, particularly since fewer fasteners need to be handled and driven or inserted and greater shear forces can be transmitted in a given joint area by fasteners in multiple shear than by fasteners in single shear.

Also, a fastener with a special head may have to be chosen to discourage, or make practically impossible, any tampering with the fastener; and again different fastener heads may be selected to allow later tightening of the joint and/or subsequent dismantling of the structure with or without special tools.

Furthermore, the fastener has to be installed in such a way that the fastened and fastening members are not spalled, cracked, split or delaminated excessively. The selection of the fastener type, shank, point, and head is often influenced by the need to eliminate or minimize such deficiencies.

In short, fastener applicability can be a prime criterion in fastener selection. Issuance of performance specifications can automatically eliminate the selection of such fasteners which cannot be located and placed efficiently under given conditions.

2.4. Physical Properties

Fasteners need to have such physical properties as to perform satisfactorily for the intended purpose under prevailing conditions.

If too short, the fasteners may not penetrate sufficiently deep to transmit the forces satisfactorily into the member. If too long, the fastener points may have to be clinched to eliminate hazards of handling; or the fastener head may back out and protrude from the surface of the nailed member as a result of the drying of insufficiently seasoned lumber, which usually is wetter inside than outside and may shrink more than is permissible along the nail shank penetrating into the wet part of the piece.

If too heavy, the stout fastener may require predrilling to prevent splitting. If too light, the slender fastener may not offer satisfactory drivability into dense material; or such a fastener may not provide sufficient contact area with the surrounding material to prevent excessive deformation or crushing of that material during shear-load transmission.

If too pointed, the long nail point may act as a wedge during driving and split the lumber. If too blunt, the short-pointed or pointless nail may shear the fibers excessively during its insertion.

If provided with too large a head, the fastener may be too conspicuous. If provided with too small a head, the head pull-through resistance may be lower than the shank withdrawal resistance, whereas both performance properties should be similar under idealized conditions.

If provided without a fillet between head and shank, the nail head may break off during driving. If provided with too large a fillet, the head may not be driven flush with the surface of brittle materials.

If provided with too thick a head rim, excessive crushing of the material below the nail head may be necessary in the flush driving of such a nail. If provided with too thin a head rim, the nail head may be deformed during hammer driving.

If square wire is twisted or a round wire is pulled, prior to the cutting, through a rotating die with a square-shaped orifice, the fastener, usually having not a round but a roundish head, is helically fluted from head to point, thus, without the desirable clearance below the head. If the fastener shank is threaded annularly, its root diameter is smaller than the wire diameter, resulting in a minimum cross-sectional shank area which provides minimum resistance to bending and shear forces. Yet, such a fastener can provide maximum withdrawal resistance if driven into side-grain lumber, since the wood fibers are forced to glide over the thread crests into the spaces between the thread flanks and the fastener can be withdrawn only if the wood fibers are sheared off by the thread crests.

If the fastener shank is provided with helical threads having a small lead angle, the cross-sectional area can be uniform along the shank: a particular advantage if the fastener is to transmit high bending and shear forces. If the fastener shank is provided with helical threads having a large lead angle, the cross-sectional area along the shank is uniform and the fastener turns during driving, thereby forming a helical thread in the wood surrounding the fastener shank. The withdrawal resistance of such a nail is limited by the frictional resistance required to screw the fastener out of the fastening material; and/or the shear resistance of the material along the helical threads crests.

In brief, that fastener has to be chosen whose physical properties can fulfill given performance requirements.

2.5. Mechanical Properties

The performance of fasteners used in building construction is critical in providing structural integrity. The forces normally encountered are bending or single or multiple shear forces, head pull-through and shank withdrawal forces, and various combinations of all as a result of eccentric loadings. Therefore, the fastener has to provide --- in addition to satisfactory drivability, that is, buckling resistance in the instance of nails and insertability in the instance of pronged and toothed connector plates --- adequate resistance to static and/or impact bending and shear forces as well as head pull-through and shank withdrawal forces.

If friction between the fastener and the surrounding material solely provides the resistance to the latter forces, the friction offered depends to a considerable extent on the elasticity and density of the fastened materials on the one hand and the shape, contact area, and roughness of the fastener surface on the other hand. The shape of the fastener can be reinforced by providing the shank with longitudinal wedge-shaped flanks, and by twisting, fluting or threading it. Its surface area and roughness can be increased by etching, barbing, twisting, fluting, and annular or helical threading the nail to such an extent that the frictional resistance is supplemented by the shear resistance of the material penetrating into the cavities of the deformed shape.

By increasing the resistance to axial forces as a result of rolling annular threads onto the shank, the resistance to bending and shear forces is decreased because the thread root diameter is smaller than the wire or shank diameter. On the other hand, by rolling helical threads onto the shank, the cross-sectional area of the threaded shank is equal to that of the non-threaded part of the shank, that is, of the wire or shank diameter. Therefore, the resistance to bending and shear forces of the helically threaded shank may be equal to or even greater than that of the plain shank because of work-hardening resulting from the threading operation.

The bending and shear resistance of a steel fastener may also be increased by hardening, that is, heat-treating and tempering the fastener. On the other hand, the transmission of bending and shear forces by the fastened and fastening materials may be increased only if these forces can be transmitted deeper into these materials as a result of the higher stiffness of the hardened fastener at high flexural deformations. Thus, more effective joints can be obtained by the use of hardened-steel fasteners --- which can often be more slender than equivalent non-hardened fasteners --- especially if a larger number of such slender fasteners can be located in a given joint area.

In contrast, the relatively soft copper and aluminum nails offer, of course, considerably smaller resistance to bending and shear forces than the non-hardened and hardened steel nails of same diameter.

2.6. Rigidity

Fastener rigidity, hence, joint rigidity, can be considerably influenced by the fastener material and fastener diameter. Soft copper and aluminum nails are more pliable than steel nails; and low-carbon steel nails are more pliable than medium-carbon steel ("stiff-stock") nails and hardened-steel nails at high flexural deformations. Since hardened nails can be smaller, usually one gauge smaller, in diameter, than non-hardened steel nails and since wood joints with a larger number of nails of smaller diameter can be more rigid than wood joints with a smaller number of nails of larger diameter, the use of hardened-steel nails can result in nailed wood joints of maximum rigidity and stiffness.

High joint rigidity is required for rigid and semi-rigid structures as well as for such structures where an apparent lack of stiffness can cause discomfort to the occupants and users of the structure. Therefore, structures can often be up-graded by improving the structural rigidity of the joints, namely, by selecting the most rigid fasteners suitable under given conditions. Yet, such fasteners must not be brittle, but are to be tough, since brittle fasteners can fail during driving or forceful insertion as well as during load transmission and, especially, during the transmission of impact loads.

2.7. Damping Capacity

Highly ductile materials offer high damping capacity to impact and shock. The use of brittle fastener in such materials could be disasterous because such fasteners could not compensate for the ductility of such materials. On the other hand, tough ductile fasteners, such as properly hardened steel nails, can provide tougher joints than regular low-carbon and medium-carbon steel (stiff-stock) nails and hardened-steel nails which are hardened improperly, hence, either too soft or too brittle.

Therefore, wherever high damping capacity is a requirement, the use of properly hardened steel fasteners can result in greater impact resistance and shock absorbtion, both of which are highly desirable especially in earthquake regions.

2.8. Compatibility

Compatibility with the environment may require the use of corrosion-resistant or non-corrosive fasteners. Failure to perform satisfactorily under corrosive conditions may result in slight or heavy corrosion of the fastener. Even if the corrosion takes place only along the fastener surface, and is of minimal influence on the fastener performance --- yet, possibly enhances the fastener performance as a result of the roughening of the fastener surface --- the corrosion by-product can cause chemical deterioration of the material surrounding the fastener in the presence of free moisture. Therefore, fastener corrosion has to be minimized and appropriate fasteners should be specified on a performance basis.

In the fastening of certain metals or dissimilar metals, a steel fastener without any corrosion protection may, under given conditions, perform fully satisfactorily; whereas, under other conditions, it may have to be electro-plated and, under more severe conditions, it may have to be galvanized. Instead of being made of steel, the fastener may have to be made of copper, aluminum, brass, bronze, stainless steel, Monel or other alloys or plastics.

Present research indicates that the coating of metal fasteners with certain plastics can provide satisfactory insulation of the fastener, hence, corrosion resistance; therefore, full compatibility with dissimilar metals. Such plastic coatings can also be effective in preventing condensation, hence, discolorations and rust spots, where the fastener can serve as a conductor of heat and cold in material acting as an insulator. The introduction of such coatings appears to be promising and justified for use under adverse conditions.

Compatibility with esthetic requirements can be another performance criterion of major importance. Hiding the fastener by countersinking and puttying of the nail hole, camouflaging it by discrete color-coating, or accentuating its appearance by contrasting color-coating or with a plastic overlay head can solve otherwise difficult esthetic problems.

2.9. Reliability

Since heat-treating and tempering of fasteners are, practically speaking, more an art than a science, it is possible that the heat-treated fasteners, or some of these fasteners in a lot, are too soft, too brittle, or not as tough as they are expected to be. Standard test methods for nails having been established (4, 5, 6). Therefore, it behooves the manufacturer of hardened-steel nails to test his nails prior to their release, in order to eliminate the use of unsatisfactory hardened-steel nails and the dangers involved as a result of their use. Vice versa, the user of hardened-steel fasteners should either require submission of a certificate by the fastener manufacturer as to their satisfactory performance or have these fasteners tested prior to their use.

Several types of performance tests have been used with which the ductility and pliability of nails can be determined (6). The selection of any of these tests and their performance can result in representative, reliable, and comparable test data within a series of alike tests; but not necessarily in directly comparable test data within a series of different tests in the light of the different nature of these tests. Performance criteria for certain non-hardened and hardened medium-carbon steel nails are being developed (7), to allow detection of too soft or too brittle nails prior to their use and, thus, to eliminate their use in assembly and construction. Similar test procedures and performance criteria need to be developed for other fasteners before full reliance can be placed on performance requirements for all mechanical fasteners used in building construction.

Fasteners transmitting bending and shear forces may continue to deform with the passage of time if overloaded. Similarly, the material surrounding the fastener is likely to continue to deform after fastener penetration with the passage of time if excessive loads are transmitted by the fastener. Such creep can lead to excessive deformation of the joint and excessive deflection and/or distortion of the structural component or structure. Therefore, it is necessary to select fasteners of such sizes which reduce such creep to the permissible minimum.

Wood shrinks and swells with changes in moisture content as a result of changes in the relative humidity of the surroundings; whereas the metal fastener is not undergoing such changes under these conditions. Therefore, the fastener is likely to protrude backward if it is not driven all the way through the fastening material. To reduce such backward movement and the resulting nail-head protrusion to a minimum, the nail should extend through the fastening material if this is feasible; the nail should be provided with an effective annular thread or helical thread with small lead angle; and the nail should not penetrate into the wet inner core of the lumber, that is, be as short as possible and still provide satisfactory holding power, if the lumber is not fully seasoned.

In the instance of repetitive changes in temperature, even if minimal, the metal fastener being a good conductor, changes its length rapidly; whereas the surrounding material, such as wood being a good insulator, may change its depth along the fastener shank slowly, if at all. As a result of such repetitive infinitesimal small or large changes in the fastener length, the nail head, and especially the head of a nail fastening metal roofing, can back out (fig. 3), if the recommendations presented in the previous paragraph have not been followed.

The metal fastener, being a good conductor of heat, can in the instance of a fire conduct excessive heat beyond the surface of the fastened and fastening members and, thus, cause deterioration of the fastened and fastening materials along the fastener shank, thereby reducing the performance of the fastener and that of the joint. To prevent excessive reduction in performance and provide the required fire resistivity, the fastener may have to be longer and possibly heavier than necessary otherwise.

With the fastener penetrating the fastened and, in certain instances, the fastening members, barriers for the infiltration of liquids and gases may be broken by the fastener, especially by a bolt in an over-size hole. Under given conditions, such penetration can be serious and will have to be avoided by the incorporation of sealing devices. They may be elastic washers under the fastener heads and/or deformations along the fastener shank and head, which serve such a purpose.

Multiple fasteners which are ductile and inserted tightly, such as nails driven without predrilling or into under-size holes, may transmit shear loads rather uniformly. On the other hand, multiple fasteners which are rigid and inserted into predrilled over-size holes, such as bolts, or into pre-drilled grooves, such as split-ring connectors, may transmit shear loads non-uniformly. If the design load per fastener is reduced sufficiently to take care of such discrepancies --- as is the case in the "National Design Specification for Stress-Grade Lumber and Its Fastenings" --- no consideration has to be given to this non-uniformity in load transmission by certain multiple fasteners. When introducing new fasteners, however, they may have to be tested in joints with single as well as multiple fasteners in order to be able to predict their performance and to establish performance criteria valid for single as well as multiple fasteners.

2.10. Maintenance and Repair

The selection of the fastener should be influenced by considerations which minimize the maintenance cost of the whole structure. If steel nails rust through a paint coat, the esthetically unacceptable rust spots may call for repainting of the whole building. On the other hand, corrosion-resistant and non-corrosive fasteners, instead of plain steel fasteners, could probably have been used initially at a negligible increase in the total construction cost. Too little emphasis is usually given to such considerations, in order to minimize initial costs, even if the long-range costs are out of the world in comparison to the otherwise nominal increase in initial costs.

Repair and alterations may require removal of members and components. If assembled with the highly effective threaded hardened-steel nails, such removal may not be feasible without destruction except in the instance of the use of such helically threaded nails with slotted heads or double heads which allow easy nail removal. The use of fasteners with special heads requiring special tools for removal can be justified at times to minimize the danger of unauthorized removal.

3. Testing for Performance Evaluation

Rarely is it possible to base the actual performance of mechanical fasteners and mechanically fastened joints solely on measurement to be used in analytical computations. The empirical approach is usually required at least in initial attempts to predict fastener and joint performance. The empirical methods include short and long-time experiences gathered with the fasteners and assembled joints as well as full-scale testing of the fasteners and joints, simulating actual field conditions.

Standard test procedures have been and are being developed by research laboratories involved in the testing of mechanical fasteners and joints assembled with mechanical fasteners, often under the auspices of the American Society for Testing and Materials (6). Close adherence to these methods is suggested in order to obtain as comparable test data as is feasible.

Such testing is possible if the fasteners can be made available for testing in order to predict their performance and that of the joints assembled with these fasteners. Yet, only too often, hand-made or simulated production samples are only available especially if the study covers new types of fasteners, the performance of which needs to be predicted in order to determine their marketability and in-place economy. The limitations of testing fastener samples, which do not represent mass-production samples, cannot be emphasized too much.

In the testing for performance evaluation, consideration has to be given to the many variables normally encountered in the field. Average test values can be misleading and typical samples need to be evaluated from every viewpoint applicable in the particular case under consideration.

To illuminate this point, it is most difficult, yet highly desirable under given conditions, to determine the effectiveness of a joint which represents the interface between two deflected and/or distorted structural elements representing parts of a structure under design load. Test data obtained for the joint of non-deformed members may be quite different from those for the deformed members in the light of the effects of superimposed loads resulting, e.g., from eccentricity.

Whereas it is desirable to arrive at design values from simplified test data for fasteners and joints assembled with these fasteners, performance requirements for these fasteners and joints need to give full consideration to such situations as are or may be encountered in the field.

4. Performance Criteria

All aspects covering applicable conditions must be scrutinized in arriving at performance criteria. It is recognized that far from all the information is available which is required to establish such criteria in the mechanical fastening in building construction. Yet, test criteria being developed for mechanical fasteners in related fields should make it possible to confirm eventually such assumptions as are being made at this time to bridge the present gap of knowledge. Thus, performance criteria being secured for stiff-stock and hardened-steel nails used in the assembly of wooden pallets (7) will throw light on the performance of similar nails used in building construction and, thus, justify the establishment of performance criteria for these fasteners in building construction.

While the time may not be around as yet to base the selection of mechanical fasteners and joints assembled with these fasteners solely on performance criteria, activities under way suggest that the opportunity will exist in the not too distant future to design with performance criteria in mind.

In the light of the fact that the negative side of the use of mechanical fastener systems is stressed in the previous paragraphs, it appears to be appropriate to emphasize their principal advantages over other fastening systems:

> The highly elastic, tough, readily available, usually relatively inexpensive, mechanical fasteners transmit forces from fastened member to fastening member by penetrating these members. Thus, loads are transferred from member cross-section to member cross-section, rather than from member surface to member surface. Such load transfers can result in highly effective, elastic, tough joints of relatively high damping capacity. These joints cause structures assembled with these fasteners to resist expected as well as unforeseen forces better than any other joints in common use today.

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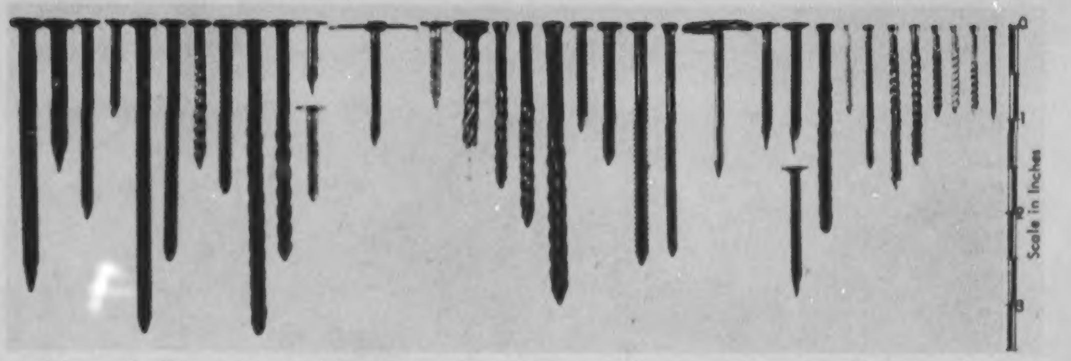
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Fig. 1 The 33 nails and 2 alternative nails used for the erection of the V.P.I. Demonstration House during 1955.

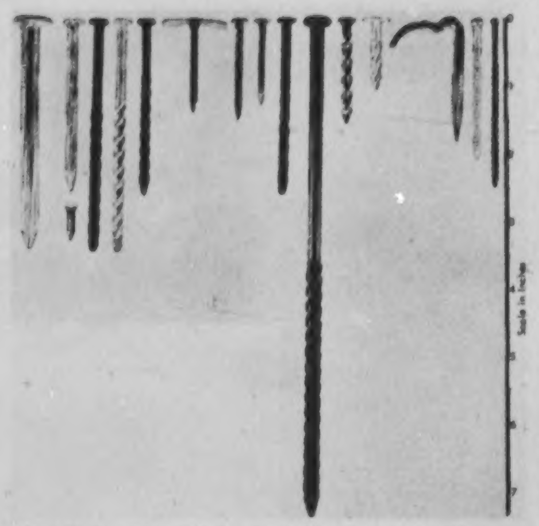
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Fig. 2 The 19 nails used for the erection of the Tech Motel in Blacksburg, Virginia, during 1961.

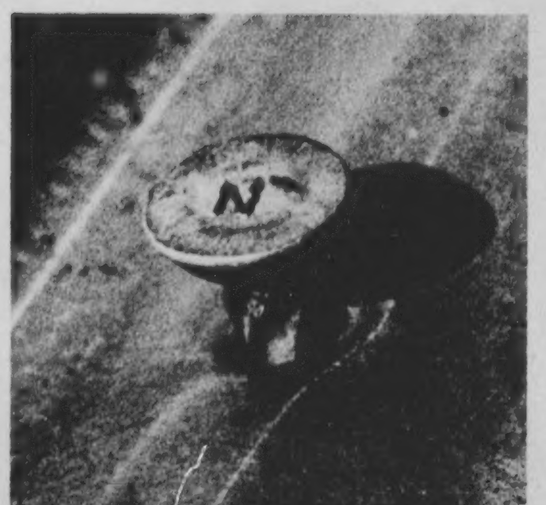

Fig. 3 Protrusion of helically threaded nail from sheet-metal roof of V.P.I. Animal Husbandry Barn.

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Performance Criteria for Composites in Building

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Composite materials for building are mainly particulate, fibrous, or laminar. Examples are to be found in buildings in various parts of the world. Performance criteria are especially pertinent because composites are frequently put together to meet specific situations. Great care is needed to make sure that the criteria accurately reflect requirements. A statement of performance criteria is of little value, unless the actual performance of a composite building component can be tested. Some tests are equally applicable to composites and to other materials, but others are specific for composites. They include, for example, the character of the bonds among constituents; the fire behavior of a composite, especially penetration, flamespread, and smoke evolution; the combined mechanical behavior; and durability. New types of tests, such as ultrasonic evaluation of bond, are needed in many instances. Standard tests may require adaptation for evaluation of composites.

Dans la construction, les matériaux composites sont principalement formés de particules, de fibres ou de stratifiés. Des exemples en sont visibles dans différentes parties du monde. Les critères de performance sont ici particulièrement pertinents étant donné que ces matériaux sont fréquemment assemblés afin de satisfaire des besoins spécifiques. Un énoncé des critères de performance est de peu de valeur, à moins que la performance réelle d'un composant de construction composite puisse être estimée. Certains essais sont également applicables aux matériaux composites et à d'autres matériaux, mais d'autres sont spécifiques aux composites. Ils portent, par exemple, sur le caractère des liaisons entre constituants, la tenue au feu globale d'un matériau composite, le comportement mécanique complexe et la durabilité. De nouveaux essais, comme l'évaluation aux ultra-sons de la liaison, sont nécessaires dans plusieurs cas. Les essais normalisés peuvent réclamer une certaine adaptation pour l'évaluation des matériaux composites.

Key words: Classes of composites; composites for building; evaluation; performance criteria; performance statement.

1. Introduction

Performance criteria, rather than prescriptive specifications, are in many ways peculiarly fitting for composite materials and composite structures in building because composites are likely to be put together to meet sets of performance requirements.

The requirements for different buildings in different environments, for different sociological and economic purposes, can be greatly different, and no generalizations for all buildings are possible. They must be drawn up with care for the specific situation, under such constraints as may be imposed by codes and regulations which may, themselves, be performance-oriented.

2. Classes of Composites for Building

Before considering performance criteria, it will be well to review the reasons for using composite materials in building and the types employed. As is true of other fields, it frequently happens that a combination of materials--a composite--has combined properties not obtainable in the components acting alone, and that composites either provide behavior not to be found in simple single-phase materials, or can provide it more efficiently or at lower cost.

Principal classes of composites employed in building are: [1][1]

Particulate: particles embedded in a continuous matrix.

Fibrous: reinforcing fibers embedded in a continuous matrix.

Laminar: layers of material bonded together and possibly impregnated by a bonding medium. A special case is the structural sandwich, consisting of two facings of relatively thin, hard, dense, strong, stiff materials combined with a relatively thick, light, less strong, less stiff core.

3. Examples

3.1. London [2]

An outstanding and almost unique example of performance specifications leading to the use of a composite panel for building purposes is the case of high-rise flats or apartment buildings for the Greater London Council (fig. 1). In connection with these buildings, the Greater London Council decided to use industrialized components to the fullest possible extent and to employ performance rather than prescriptive specifications. The cladding panels on outside walls of the buildings were selected for especial treatment.

Instead of specifying materials, the following performance requirements were laid down:

1. Ability to withstand 20 psf uniform load, equivalent to approximately 80 mph winds. Allowable deflections were specified, together with percent immediate recovery after load removal.

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[1] Figures in brackets indicate the literature references at the end of this paper.

2. An overall heat transmission coefficient, U, not greater than (0.20 Btu hr^{-1} ft^{-2} $deg^{-1}F$)
3. An average acoustical attenuation factor of 35 decibels.
4. Self-extinguishing, under flamespread test, utilizing the British fire test tower.
5. At least one hour resistance to fire penetration.
6. Minimum weight, to reduce the amount of supporting structural steel, and to reduce foundations in relatively poor soil.
7. Minimum thickness, to increase the usable floor space.
8. Minimum maintenance over the expected life of the building. No specific materials were prescribed.

From the foregoing stipulations, a composite panel emerged after considerable research and development. It had the following composition:

1. One story high (approximately 2.7m) (9'-0") by 2m (6'-8") wide.
2. A press-molded outer shell of random glass fiber reinforced polyester, 2.3mm (0.09") thick, heavily loaded with mineral filler, to obtain self-extinguishing characteristics.
3. A baked-on titanum dioxide pigmented polyurethane exterior finish on the shell to provide the minimum maintenance called for. The finish is expected to be durable in the London atmosphere, polluted with urban industrial gases, but not unduly strong in ultra-violet radiation.
4. A filling, approximately 75 to 100mm (3" to 4") thick, of lightweight wire-reinforced foamed concrete weighing approximately 25 pcf, cast into the shell. A flexible bond layer of epoxy and urethane was designed to hold shell and core together but to allow for differential movement caused by temperature fluctuation.
5. An inner facing, applied after the core had cured and dried, consisting of 13mm (1/2 in.) thickness of gypsum reinforced with wire and asbestos fiber. The facing was bonded to the core with a layer of bitumen which also acted as a vapor barrier.

This factory-produced composite panel met all the requirements. It was approximately one-third as thick as standard masonry walls and weighed approximately 15 to 20 percent as much as conventional masonry or standard precast concrete panels. Six panels could be preassembled to the supporting steel and erected quickly as a unit. For the volume of panels projected, the combination of speed of erection, reduced weight of supporting frame, and reduced foundation resulted in an in-place cost estimated to be competitive with or less than conventional construction in those high-rise buildings.

3.2. Boston

In Boston, the outer walls of a twelve-story building are faced with story-high, 75mm (3 in.) thick sandwich panels consisting of a polyurethane foam core approximately 25mm (1 in.) thick surrounded by particulate composite facings of silica sand and other mineral aggregates in a matrix of polyester resin, faced on one side with exposed stone aggregate (fig. 2). This is a concrete based on resin instead of portland cement. Facings are reinforced with a heavy woven glass fiber fabric; the whole panel has steel reinforcing bars interspersed at edges and strategic internal points such as around openings. The 75mm (3 in.) thick composite panels are lighter and thinner than standard stone masonry or precast concrete faced wall construction, but meet the wind-loading, thermal, acoustical, and fire requirements.

3.3. Dwellings

In various places throughout the world, prototypes and production models of dwelling houses employing glass-fiber reinforced plastics shells, combined with other materials, are being produced. In each case, it is the combination of materials, usually in a composite structure, that meets the performance requirements. Similarly, molded fixtures such as combined bathtub with surrounding walls, made of fibrous composites faced with a thin layer of thermoformed plastic sheet, are making their appearance. Again, it is the combination of materials that meets the performance requirements.

4. Performance Statement

The Greater London Council panels illustrate the application of performance requirements in the selection of a combination of materials to perform a given task. Evidently, requirements must be drawn up with considerable care to make sure that the resulting product will provide the performance actually wanted in service, i.e., that the statement of performance requirements accurately reflects the service demands. In the case of the London panels, several performance requirements were set forth specifically and several in general terms. Specific requirements covered wind load, thermal transmission, acoustical attenuation, and fire. General requirements pertained to weight, thickness, and maintenance. Accompanying these physical statements were drawings which set forth dimensions and exterior contours of panels with and without windows, thereby establishing the sculptural pattern of the building wall but not color and texture. These came from the choice of white pigments in a baked-on coating for maximum durability, resulting in a white glossy finish. The total catalog of performance requirements, therefore, was a combination of written and graphical statements.

5. Testing

It has been pointed out, notably in the conferences of the Building Research Advisory Board, BRAB, on the Performance Concept in Building, that a statement of performance requirements is relatively meaningless and sterile unless the actual performance of a component resulting from such stipulations can be checked by test. In the case of composite materials, this can be particularly difficult because not only must the properties of the constituent materials be checked, but their behavior in situ in the composite, their interactions with each other, and the overall behavior of the composite must be ascertained.

Some tests are broadly applicable to composite and non-composite materials. A loading test on a building panel, for example, is essentially the same for all kinds of panels. A thermal transmission test, an acoustical attenuation test, a flamespread test, and a fire penetration test are essentially the same, no matter what the composition, even though the behavior of the unit is obviously influenced by its constituents.

Other tests depend strongly upon composite behavior. For example, a tensile or bending test on a block of cast polyester resin does not accurately forecast how that same resin will behave in a fibrous composite consisting of flass fibers embedded in the polyester. The composite must be tested, and a special test or test speciman may be required.

The flamespread and fire penetration characteristics of a polyester concrete cannot be foretold by fire tests of the polyester by itself. The tests must be performed on the composite.

The soundness of adhesive bonds is particularly important in the behavior of laminates of all kinds, including sandwiches. It is also important in fibrous and particulate composites. Such bonds must be tested in situ, preferably by non-destructive means. Pioneering work in ultrasonics, reported to ASTM [3], has led to a variety of non-destructive ultrasonic bond testers, but much still remains to be done, especially in non-planar composites such as fibrous and particulate. Similarly, porosity, percentage composition of composites, and distribution of components materials in a composite are all important in determining their behavior, and non-destructive tests are needed. These tests necessarily must be performed on the composite, not separately on the constituents.

Several features of composites for building and the performance requirements for them are worthy of special note. Among them are dimensional stability, some aspects of fire, and durability.

6. Dimensional Stability

Differences in expansion and contraction with changes in temperature, moisture content, or stress, can cause internal strains leading to warping, bowing, twisting, buckling, and dimpling of surfaces in a composite material. Interfacial stresses can be severe, as, for example, in the bond lines of laminar composites, and at the interfaces of particles or fibers and surrounding matrices. These are especially marked where abrupt changes occur, as at the ends of fibers if these are not tapered, and wherever differences in elastic moduli and other elastic constants of adjacent materials are large, as is quite commonly the case. An example is the structural sandwich used as the outside wall of a building. The thin exterior facing undergoes appreciably greater changes in temperature than does most of the core, but the outer part of the core changes more than the inner part, and the inner facing may change little, if at all, in a temperature-controlled indoor environment. The sandwich, as a whole, tends to bow or curl, i.e., to become convex or concave with dimensional change. Both shear and tensile stresses are induced which may result in failure and delamination in the bond line or in the weakest component, such as the core.

Performance requirements can be written to limit the amount of bowing, cupping, and other dimensional changes that will be tolerated. Such requirements must be realistic and recognize that some changes are inevitable with all materials available for building, but with realistic values established, the producer of a composite panel can select his materials and combinations to meet the conditions. The designer, in turn, in collaboration with the materials specialist, can select configurations, such as curved rather than flat surfaces, that accommodate dimensional changes without being evident or leading to distress.

7. Fire

Although fire requirements for composites should be essentially the same as for any other components or materials that perform the same function, composites may present some aspects that call for careful attention in the setting up of performance requirements. For example, if surface flamespread is the overriding consideration, a composite can be put together that has the appropriate surface characteristics. If fire penetration resistance is the criterion, then a different combination of materials will be needed. If, as is often the case, flamespread and penetration are both important, still another combination may be required.

Table 1 gives a few selected values of flamespread, fuel, and smoke evolution, showing the considerable spread obtained with various compositions.

Performance criteria evidently must be written with the requirements of any specific application in mind. Smoke evolution figures do not distinguish among the constituents of the smoke, whether noxious, toxic, or otherwise.

Perhaps the most serious lack in many current specifications has to do with smoke and toxic or noxious gas evolution. Various classes of surfaces have quite specific flamespread restrictions, but the requirements are silent with respect to smoke and toxic or noxious gases. This may be a reflection of a lack of consensus, and of dissatisfaction with existing test methods, but one result is that materials and composites have evolved that meet flamespread limitations, but frequently at the cost of increased smoke and toxic or noxious gas evolution. Performance criteria are needed to cover these points [5]. Fire officials are becoming increasingly concerned with smoke. Some cities have issued tentative smoke limitations. Table 2 summarizes a few [5].

8. Durability

Of all the attributes required of a building component, whether a composite material or otherwise, long-time durability is often both the most important and the most difficult to specify. It is also the most difficult to measure and predict on the basis of short-time tests.

The London panels illustrate this point. Durability to outdoor exposure was specified only in general terms, no specific numerical requirement could well be set up. The baked-on pigmented coating on the press-molded glass-fiber reinforced polyester shell was relied upon to furnish resistance to weather. Because the shell was there, a lightweight concrete foam, not weather-resistant, could be employed to provide the low U-factor, most of the acoustical attenuation, and resistance to fire penetration. The reinforced gypsum inner face was relied upon to provide durability against the general wear and tear of indoor occupancy which the somewhat friable concrete foam core would not withstand.

Performance requirements for durability must be carefully formulated. What is important: color retention, loss of gloss, permeability, erosion, corrosion, decay, wear resistance, texture, resistance to vibration, retention of thermal or acoustical characteristics or both, or what combinations of these? Can recoating or other regeneration be expected or tolerated from time to time? All of these considerations, as set forth in performance requirements, have a bearing on the combination of materials in a composite to meet them.

The BRAB point respecting the importance of tests to validate performance is especially pertinent here. Short-time tests to predict long-time performance are especially needed for composites, because it is not generally sufficient to test the component materials, it is the behavior of the composite that needs to be ascertained, and this may be quite different from that of the components by themselves. The need for reliable short-time tests to predict long-time behavior is not restricted to composites, but in many ways, it is peculiarly urgent, especially if the objective is to meet performance requirements.

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Table 1. Flamespread Tests (ASTM E-84)

Glass-fiber reinforced plastics			
	Underwriters' Laboratories [4] Flamespread	Fuel	Smoke Evolution
1	65	10	over 500
2	25	--	250
3	55-70	10-15	over 500
4	20	--	300
5	65	10	over 500
6	75	15	over 500
7	20	--	860
8	17	--	760
9	17	--	920
10	200	64	123
Polyester Concrete			
	(Manufacturer's Data) 3	0	55

Table 2. End Points on Smoke Density (ASTM E-84)

	Classification		
Building Code	Class A (or I)	Class B (or II)	Class C (or III)
San Francisco	25	200	450
Philadelphia	--	---	225
New York City[a]	25	50	100
Michigan[b]	50	125	200
Texas[c]	25	75	200

[a] Applies to interior finishes in exits, corridors, and institutional occupancies.

[b] Applies to interior finishes in school buildings.

[c] Applies to floor coverings in nursing and convalescent homes. In certain conditions, intermediate levels are established at 60, 100, 150, and 175.

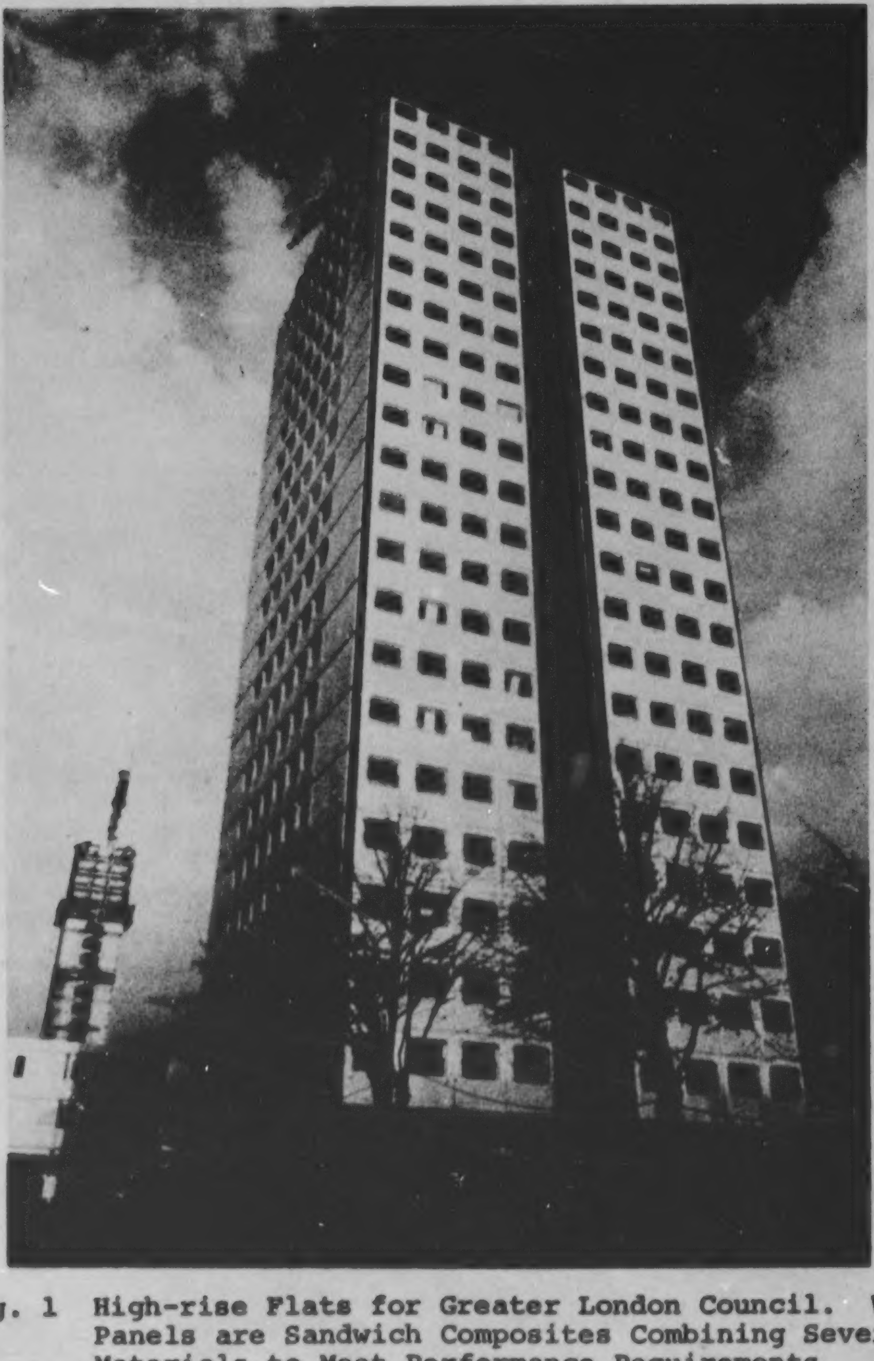
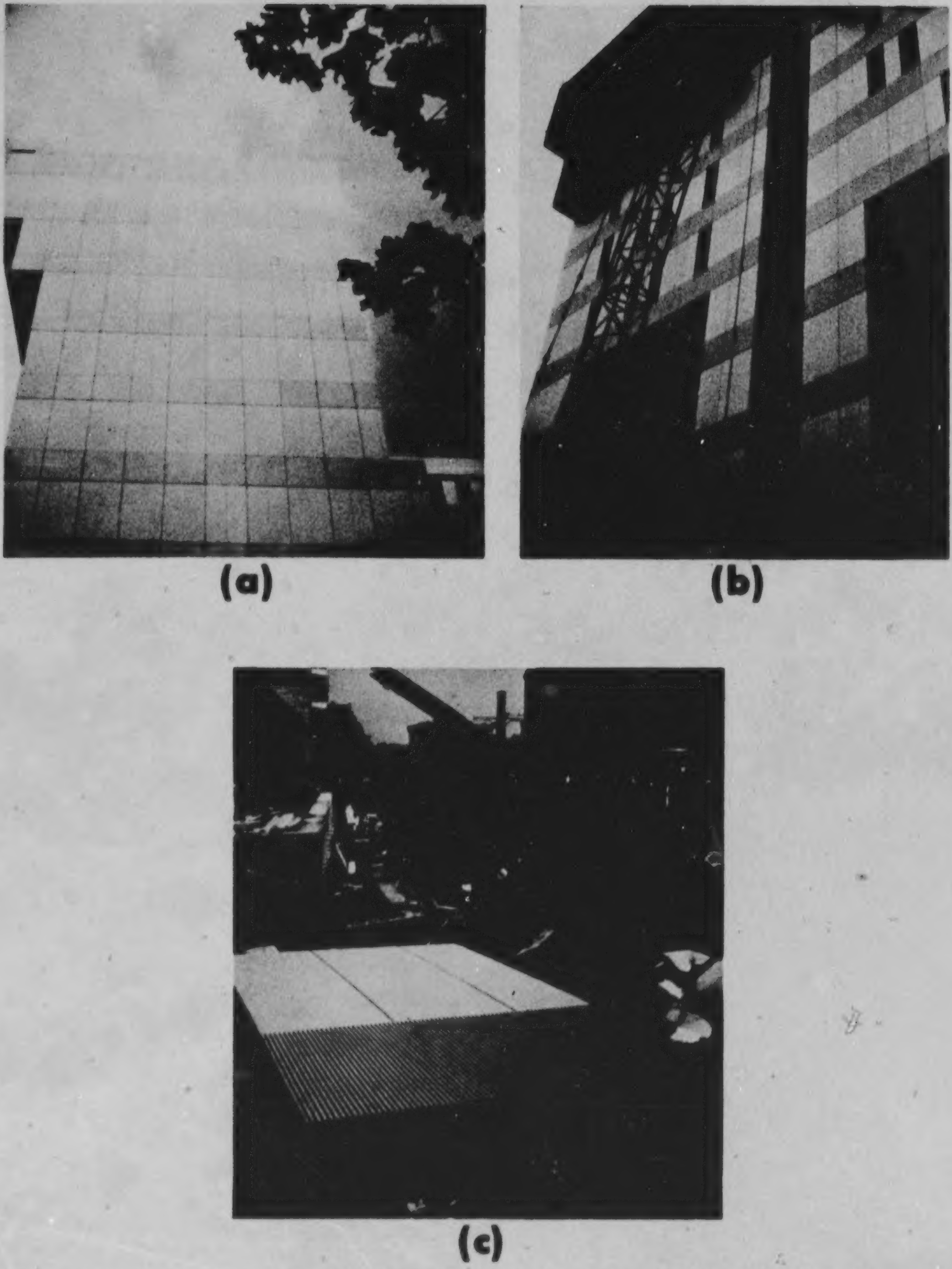


Fig. 1 High-rise Flats for Greater London Council. Wall Panels are Sandwich Composites Combining Several Materials to Meet Performance Requirements.



(a) (b) (c)

Fig. 2 Wall Panels of Harvard Medical Center Building, Boston. (a) End Wall; (b) Rear Wall with Windows; (c) Wall Panel, Consisting of Particulate Polyester Concrete Facings on Polyurethane Core.

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Basic Problems and Conditions of Long Term Performance of Materials and Structures

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Appropriate choice of materials for structures of all sorts must be based on their properties and long term performance in specified conditions of their application. Besides the main mechanical physical factors, factors concerned with the pore system in relation to the possibility of water or gas penetration must be considered as basic properties in the study of long term behaviour of any material in natural weathering or other conditions. Actual state of standards concerned with humidity and water permeability of materials is analysed. Absorption, permeability and capillary elevation are considered as the main characteristics of materials.

Absorption test - its purpose and methods are discussed in the light of the mechanics and kinetics of water penetrating into a porous body. Some standards British, Russian, American and Czechoslovak are then quoted and analysed as to their interpretation and compliance with the need to describe the pore system effectively. The need of scientific base of such tests is stressed.

Permeability test - its purpose and methods are given with special emphasis to the need of providing us with the coefficient of permeability. British, Russian, German and Czechoslovak standards for testing are then surveyed from this point of view.

Capillary elevation test in relation to the importance of the capillary elevation head is analysed and Czechoslovak standards are quoted.

Mechanics and kinetics of water permeation into materials,

its factors and their determination are considered as to their effect and importance for their performance in structures. Both steady and unsteady flow of water are considered in relation to the determination of the coefficient of permeability. Capillary properties of the pore system should be provided by test. The importance of these characteristics for the analyses of tests as well as of practical cases is then stressed by cases of practical application.

Le choix approprié des matériaux de constructions de tout genre doit se fonder sur leurs propriétés et sur leur performance à long terme dans les conditions particulières de leur application. A côté des principaux facteurs mécaniques et physiques, on doit considérer, dans les systèmes de pores, les facteurs ayand trait à la capacité de pénétration par l'eau et les gaz comme essentiels pour l'étude de la performance à long terme de n'importe quel matériau exposé aux intempéries naturelles ou à d'autres conditions. On analyse ensuite l'état présent des normes relatives à l'humidité et à la perméabilité des matériaux. L'absorption, la perméabilité et le capillarité sont considérées comme les caractéristiques principales des matériaux.

Essai d'absorption: but et méthodes font l'objet d'une analyse à la lumière de la mécanique et de la cinétique de la pénétration de l'eau dans un corps poreux. Des normes britanniques, russes, américaines et tchécoslovaques sont citées et analysées en regard de leur interprétation et de leur conformité à la nécessité de décrire le système de pores efficacement. Le besoin d'une base scientifique pour de tels essais est souligné.

Essai de perméabilité: but et méthodes sont donnés en marquant le besoin d'un coefficient de perméabilité. Les normes d'essai britanniques, russes, allemandes et tchécoslovaques sont passées en revue sous cet aspect.

Essai de capillarité en relation avec l'importance de la hauteur d'ascension capillaire de l'eau. Les normes tchécoslovaques sont citées.

Les facteurs mécaniques et cinétiques de la pénétration de l'eau dans les matériaux sont considérés et évalués en rapport avec leur effet et leur importance quant à la performance de ces matériaux dans les constructions. Pour établir le coefficient de perméabilité on considère aussi bien l'écoulement d'eau permanent que l'écoulement transitoire. Les propriétés capillaires du système de pores devraient être évaluées par des essais. Des cas d'application pratique démontrent l'importance de ces caractéristiques dans l'analyse des essais, ainsi que dans les applications pratiques.

Key words: Capillary elevation (head); coefficient of permeability; kinetics of deterioration; open pores; steady and unsteady flow; tests of absorption, permeability and capillary elevation.

1. Introduction

Technically effective and economical long term performance of all engineering structures is becoming a decisive factor in the selection of available, appropriate, or optimum structural systems and materials. This decision must be based on perfect knowledge of mechanical, physical, and chemical properties of materials and their development under conditions of their expected long term use. External conditions or environment are determined mainly by climate and soil (with either natural or artificial, underground water) or manufacturing processes as in industrial buildings (storages or processes) and/or in agriculture.

The long term performance of structures results from the original state and properties of the structure and materials, and from the changes and deteriorations of these original properties by external agents.

The choice of suitable materials or combination of materials in any structure has to be based on the careful consideration of its performance given by:

a) supporting all sorts of loads followed by strains, deformations and fissures,
b) transmission of heat and sound followed by deformations, strains and eventual rupture,
c) penetration of liquids or gases through the pores with
  - volume changes and strains,
  - changes of physical and mechanical properties,
  - all sorts of deterioration based on the presence of water and chemical agents (frost, leaching out, crystallisation of salts etc.).

For any comprehensive study, and especially forecast of the final effect on the material behaviour, and for the design of structures and their elements, appropriate basic properties of the material have to be considered together with the mechanics and kinetics of processes in specified and well-defined conditions.

Natural weathering conditions differ greatly even at the same location, and their long term effect - to be considered in design - has to be anticipated and based on:

a) basic mechanical and physical properties of materials (provided by tests),
b) theoretical analysis of the mechanics and kinetics of the deteriorating processes,
c) the results of appropriate accelerated tests,
d) the evaluation of external conditions anticipated during the lifetime of the structure.

Actually there is no exact procedure which deals with this complicated problem. However, the scientific access to the problem, especially its kinetics, provides us with the most reliable means. The penetration of water or gas into pore-system is at the very base of this problem.

2. Actual state of standards concerned with humidity and water permeability of materials

The nature and extent of the system of open continuous pores (communicating with the surface) in engineering materials is of basic importance in the behaviour of any such material especially in structures exposed to external conditions. In case of intermittent exposure to water it is important for the depth of water penetration as well as for the relative humidity of the material. In case of permanent exposure it is important for the effective seepage of water through such a material.

As far as penetration of water is concerned - the specifications or standards should consider and specify appropriate methods of testing for: absorption, permeability, and capillary elevation of water in materials.

Generally speaking, all the methods of testing applied still are empirical in nature and while giving a quite good means for comparison do not determine the physical characteristics necessary for any comprehensive interpretation of tests and for design. Physical characteristics are necessary for appropriate study of processes dependent on water penetration and its kinetics, as well as for the rational design of structures.

2.1 Absorption tests

This test is very attractive primarily because of its simplicity and is used practically in every country although in different arrangements and with different test procedures (Fig.1.).

The purpose of the absorption test is to determine the volume of water-accessible pores under small water-head. This is important especially for assessing thermal properties and the durability of materials.

Water penetrates into open capillary systems of pores by capillary forces (capillary elevation h_o - for materials wetted by water) and by hydrostatic pressure (h_x). Meanwhile the air is forced out by water to either other areas inside the specimen body or out of it (if under partial immersion). Under these conditions, which depend on the size of specimen, the penetration of water is not uniform and any comprehensive interpretation of results is difficult, especially when the depth of penetration is not known. Further difficulty is given by the fact that the total hydraulic head ($h_r = h_o + h_x$) is not known exactly.

Generally, measured absorption is expressed by increase in weight of the specimen either for a limited (defined) time, or for absorption to "constant" weight.

The results of tests have only relative, comparative value - in relation to other such tests - with no possibility to derive physical characteristics of the pore system accessible to water. The reliability of the volume of accessible pores (either absolute or relative) thus measured is conditioned on the possibility of air escape. Vacuum treatment before immersion might help to improve the results from this point of view.

For the possibility of water permeability factors determination by these tests, the kinetics of absorption (permeation of water) has to be ascertained [1, 3][1]. The British method of water absorption test after 10 minutes and 24 hours of submersion represents a step forward. This absorption should not exceed 2,5% after 10 minutes and 6,5% after 24 hours. For a homogeneous material and the possibility of free penetration of water into the material, with no counter-pressure of enclosed air, this relation is given in Table 1.

Table 1. Relative depths of water penetration into a poreous material.

minutes	10	40	90	160	250	360	1440 (24 hrs)
relative depth (or weight increase)	1	2	3	4	5	6	12

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[1] Figures in brackets indicate the literature references at the end of paper.

When the test specimen is small and there is no path for the escape of enclosed air in front of the penetrating water tests have shown that the rate of penetration is reduced as well as the resulting depth. Even in this case the relative increase in weight is dependent on the size of the specimen, and no physical characteristic such as the coefficient of permeability **k** may be estimated without knowing the depth of penetration and size of the specimen. For this reason, special test specimens are used with great advantage where:

a) the air can escape from the specimen,

b) the depth of penetration may be measured even during the test without the necessity to break up the specimen before the end of test, (Fig. 2.)

c) the mean coefficient of permeability **k** may be calculated as well as other characteristics,

d) the homogeneity of the specimen may be assessed and characterized.

Survey of some standards

British Standards

BS 1881/1970 Methods of testing hardened concrete - introduced the test for determining the initial surface absorption of concrete in addition to the normal test for water absorption by complete immersion of the specimen in water. The first case gives the rate of flow of water into concrete at the start, when the air can escape from the sample on its opposite face. In the second case, - normal test for water absorption - only the weight increase is stated, after correction for the size of specimen (length of a 75 mm core). The thin surface layer of concrete is generally affected somehow by external conditions (drying, carbonation etc.) - and cannot be taken as valid for the whole thickness or depth.

Several British Standards as:

BS 368/1956 - Precast concrete flags,
BS 1308/1957 - Concrete street lighting columns,
BS 340/1963 - Precast concrete curbs, channels, edgings and quadrants,
BS 556/1966 - Concrete cylindrical pipes and fittings,

apply the criterium of maximum 10 minute and 24 hour absorption of water of 2,5% and 6,5% by weight respectively. For homogeneous materials, these figures have no meaningful proportion. Weight increase without the corresponding depth of penetration does not describe the pore system sufficiently.

Russian Standards

GOST 12730/1967 leads to the relative quantity of water (weight) absorbed by a specimen submerged gradually by 30 mm so that the water level covers the specimen by 10 mm after 3 hours' time. The weight is measured every 24 hours up to a constant weight (ΔG max. = 0,2% G_0). The water penetrates into the specimen mainly by capillary forces with the possibility for the air escaping only partly before the complete submersion.

American Standards

ASTM describes absorption tests for different construction materials natural and artificial (natural stone, aggregates, bricks, pipes, tiles, masonry units etc. - C97, C121, C127, C128, C67, C112, C301, C140, C497). Generally the weight increase after a period (24 hrs, 48 hrs) of full immersion is stated. Boiling is also applied for removing air from the pores.

Czechoslovak Standards

CSN 731316/68 Determination of humidity, absorption and capillary elevation in concrete. The specimens are submerged gradually starting with 3 cm of water so that the water level covers the specimen by 1,0 cm after 3 hours time. The absorption of water is given by weight increase in percent. The weight is measured every 24 hrs up to the constant weight (ΔG_{max} = 0,1% G_0).

Owing to the laws of water penetration, especially its kinetics, the results of such tests have no precise physical character and may serve only for comparison with other materials. They have only empirical value without any possibility to make any interpretation as to basic physical properties of the pore system.

Although such empirical tests play an important role in the simple, effective, and rapid control of materials in fabrication, pits and quarries, or on the building site, they cannot help in the development, research, and specialized design of materials and structures where the penetration of water or water vapor (permeability), and durability in aggressive conditions are of primary or great importance from the point of view of long term performance of materials and structures.

Especially in very complicated, very severe, and hazardous conditions, and in case of required long term effective service (control of humidity) and durability in external aggressive conditions, it is necessary to base objective judgements not only on accelerated tests, but necessarily also on basic properties of materials and the mechanics especially kinetics of basic processes.

On the other hand it is practically impossible to make any comparison of tests and of practical results between different countries. Besides special comparison methods - which could be introduced, although with some difficulties - methods of testing leading to exact physical characteristics may help a great deal in leading the way to organized and concentrated effort of all nations in technical progress and its economical attainment.

In spite of these discrepancies, the kinetics of gradual water penetration into concrete or other material may be a good guide for selection of appropriate materials, especially when the form and size of specimen is well defined and the waterhead is given.

2.2 Permeability test

The main purpose of this test is in the determination of the coefficient of permeability, k, necessary for any exact control of a material in relation to the requirements considered in the design. On the other hand the coefficient of permeability, k, of a material considered by the designer should be based on preliminary tests.

Methods of test based either on unsteady or steady flow of water through materials with a continuous system of pores may be applied. (Fig. 3.) The unsteady flow may be classified also as undirectional absorption of water with the possibility of enclosed air escaping on the opposite face of the material. This case occurs in practice in cases of one-sided exposure to water (tiles, slabs etc.). Under long term exposure to water, the state of unsteady flow converts into the steady state of flow which is normally applied for laboratory methods of testing materials' permeability to water. This method may be applied only to fine-grained materials and small thickness of specimen.

Without speaking about the factors influencing the penetration of water through the pores in the material, it is important to have the possibility of calculating the coefficient of permeability k as the characteristic of the material from the point of view of water permeability. Not all methods lead to this important characteristic.

Survey of some standards

British Standards

BS 473,550 : 1967 - for concrete roofing tiles and fittings - describes a method of testing under a water head of 20 cm and states that at the end of 24 hours the amount of water flowing into or through the tiles shall not exceed:

0,00126 cm^3/min/sq.in or 0,00063 cm^3/min/sq.in.

Owing to the fact that the depth of penetration (Fig.3.) is not measured during the test - this method can lead to the coefficient of permeability only for steady flow of water through the tile.

Appropriate values of the permeability coefficient k based on the rates of flow given by this Standard differ for different thicknesses of the tiles.

Specifications for cast or reconstructed stone state maximum rates of penetration in cm^3/cm^2/sec. of water after 5 minutes, 1,2 and 24 hours.

Russian Standards

GOST 4800/59 Concrete for hydraulic structures is based on the unsteady flow of water through a sample (cylinder or core Ø 15 cm, h = 15 cm) with the water head increasing every 8 hours by 1 kp/cm^2 (Fig.4.). The water penetrates from the bottom. The permeability of concrete is given by the water-head for which the water penetrated through the sample. Even for this case of a complicated water-head loading, it is possible to calculate the appropriate coefficient of permeability k. This possibility is not considered by the GOST itself.

German Standards

DIN 1048/68 is based on the unsteady flow of water through cylindrical concrete samples, the dimensions of which depend on the maximum size of aggregate. The water penetrates from the top of the sample. The time and the water-head (Fig.4.) are registered up to the moment of water penetration. After the test, the specimen is broken to get a picture of the water-line. The coefficient of permeability k is not considered.

Czechoslovak Standards

ČSN 73 13 21 /68 is based on the unsteady flow of water as the Russian and German Standards, and with a different water-head load regime (Fig.4.), but practically the same criterium for the degree of "impermeability". The water-line on the broken surface of the sample is given in the report, but the coefficient of permeability k is not considered.

2.3 Capillary elevation test

Capillary elevation of water in building materials and walls is of great importance especially from the point of view of long term performance of buildings, especially houses. Capillary penetration of water into walls make many old houses unhealthily damp, and cold due to the loss of heat insulating properties, and creates conditions for frost and other damage. It is important, too, to make appropriate and precise interpretations of absorption or permeability tests under low water-head, where the capillary elevation head h_o is of great relative importance (Fig.1,2). The test should lead to this value h_o and thus provide the possibility of precise and correct interpretation of test results, and with correct values of the permeability coefficient $\underline{k}$ necessary for any design purposes. Only very few examples of standards for this test may be given.

Czechoslovak Standards

ČSN 73 13 16 /68 is based on increasing weight of concrete test specimen immersed by its base in water (1 cm). The weight is measured at intervals eventually up to 28 days - and if possible the capillary elevation h_o also is given.

Without correct interpretation, especially of the capillary elevation h_o at precise intervals, reliable results necessary for correct application, especially for long term behaviour of materials exposed to the possibility of capillary effects of water, cannot be obtained.

3. Mechanics and kinetics of water permeation into materials, its factors and their determination

The presence of water in open pores of a material in structures, especially in case of severe exposure, has generally an ill effect on its properties and long term behaviour. The variation of the water content has, therefore, to be analysed in relation to important or decisive external effects, either unfavourable or aggressive. Any instantaneous state of water content is the result of successive water gains and losses. The kinetics of both these phenomena should be at the base of any thorough study. The water gain generally has a deleterious effect on the behaviour of a material (lost insulating property, frost action, action of aggressive salts). This state makes the kinetics of water penetration into the system of open pores and through such pores most important.

Two cases must be considered:

a) unsteady flow of water through a poreous body. This is the most frequent case of water penetrating into concrete from its surface. The water-head is generally constant, but the depth of penetration and therefore the rate of water absorption varies with time.

b) steady flow of water through a poreous body as through walls of galeries, tunels etc. This flow is generally preceeded by unsteady flow before the water penetrates through the whole thickness.

For both cases, it is necessary to know the coefficient of permeability k in the Darcy's law:

$$v = k \cdot I = k \cdot \frac{h_r}{x} \qquad (1)$$

where: h_r - effective water head
x - depth of water penetration.

All the laboratory tests of permeability should lead to this physical characteristic for open continuous pore-systems necessary for studies and design.

In the case of unsteady state of flow:

$$v = k \cdot \frac{h_r}{x}, \quad dx = v \cdot dt, \quad x^2 = 2\,k\,h_r\,t \quad \text{and}$$

$$k = \frac{x^2}{2\,h_r t} \qquad (2)$$

For any h_r, x and t have to be measured for the calculation of k.

In the case of steady state of flow:

$$v = k \cdot \frac{h_r}{l}, \quad q = f \cdot v, \quad \frac{q}{f} = k \cdot \frac{h_r}{l} \quad \text{and}$$

$$k = \frac{q \cdot l}{f \cdot h_r} \qquad (3)$$

where q - water flow per sec,
f - flow section,
l - thickness of specimen.

Different experimental arrangements are possible for the test so that the coefficient of permeability k can be obtained from the results. This is valid also for the case of a more complicated regime of test as shown in Fig.4, where only the corresponding time t and depth of water penetration x are given.

A further step to increase the reliability of test results and the determination of the physical characteristics of the pore-system is given by the determination of capillary properties of the pore system. From the point of view of water penetration they can be well described by capillary elevation h_o. Owing to the very complicated character of the pore system, h_o has a rather statistical meaning and is represented by capillary elevation after a very long period (Fig.5.). Capillary elevation h_o is a very important part of the effective water-head: $h_r = h_o + h$ (Fig.1) especially in cases of low real water-head h as in the case of absorption tests.

On the base of these theoretical relations shown elsewhere / 3 / the modified absorption test (Fig.2.) was introduced and applied for the determination of the coefficient of permeability k on specimens providing for the escape of air and for the possibility to observe continuously throughout the test the depth of water penetration on 2 faces of the specimen which were provided with transparent, impermeable films. This method of measuring the depth of water permeation may be applied also to the test of unidirectional permeability in the unsteady state of flow. These and other details were also shown elsewhere / 5 /.

It is important both for the practice (design) and for research to base our analysis on physical laws and characteristics. For this possibility, therefore, especially the laboratory tests have to be arranged properly so that determination of such characteristics can be accomplished.

Consistent application of even simple laws for the penetration of water (or vapor) through materials provides the possibility of better understanding and interpretation of tests, and when applied to practical problems, the possibility of reliably based specialized design of structures for factors other than load.

The kinetics of water penetration into materials is the first and probably most important step in the scientific study of deterioration kinetics by many aggressive factors (especially in underground structures).

On the basis of the characteristics of the continuous pore system we have the possibility of calculating how long it will take before the water penetrates through a wall of an underground structure, and what will be the rate of water percolation. On the other hand, for a given admissible inflow of water the appropriate impermeability (coefficient of permeability $\underline{k}$) of the material and its thickness can be specified and designed.

In case of aggressive waters, an objective idea can be gained as to the extent of long term deterioration by aggressive factors that can penetrate into the material with water. This is the first step of any objective evaluation of long term deteriorating effects on materials of structures.

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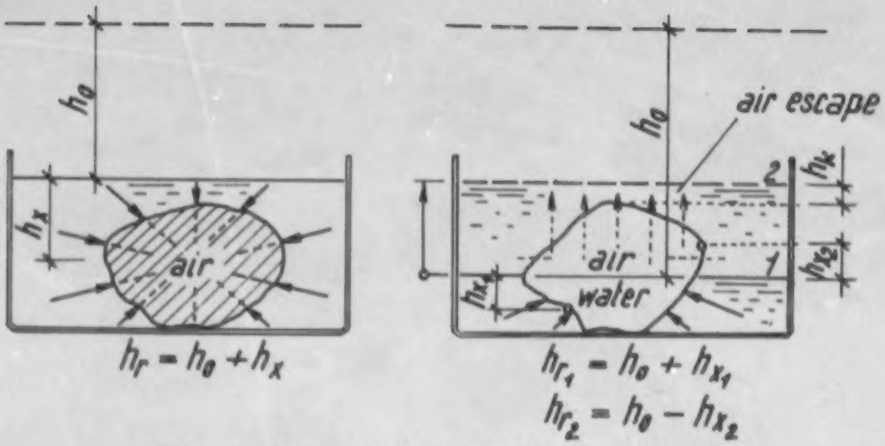
h_0
air escape
h_x
air
2
1
water
h_{x_1}
h_{x_2}
$h_r = h_0 + h_x$
$h_{r_1} = h_0 + h_{x_1}$
$h_{r_2} = h_0 - h_{x_2}$

Fig. 1 Normal (standard) absorption test

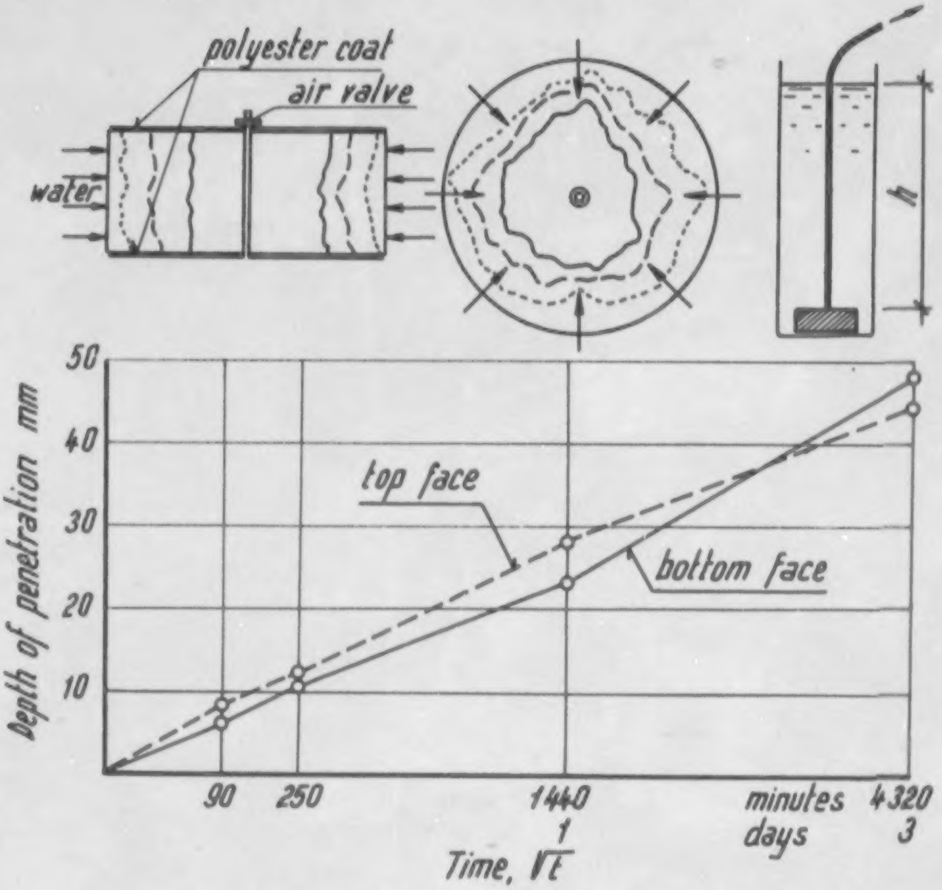

Fig. 2 Modified absorption test

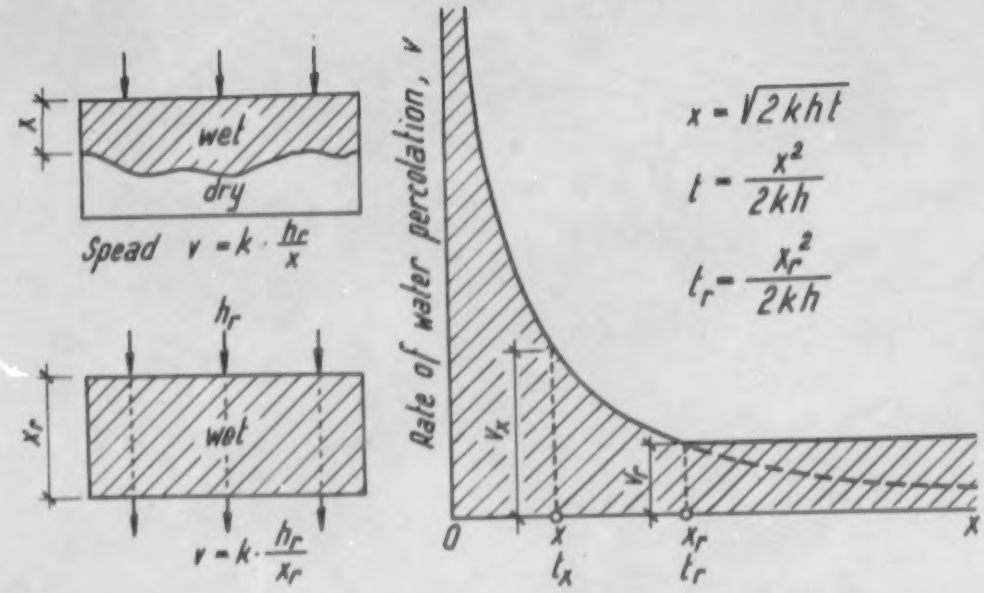
x
wet
dry
Spead $v = k \cdot \frac{h_r}{x}$
h_r
x_r
wet
$v = k \cdot \frac{h_r}{x_r}$
Rate of water percolation, v
$x = \sqrt{2kht}$
$t = \frac{x^2}{2kh}$
$t_r = \frac{x_r^2}{2kh}$
v_x
v_r
0
x
t_x
x_r
t_r
x

Fig. 3 Steady and unsteady flow of water through continuous pores of material

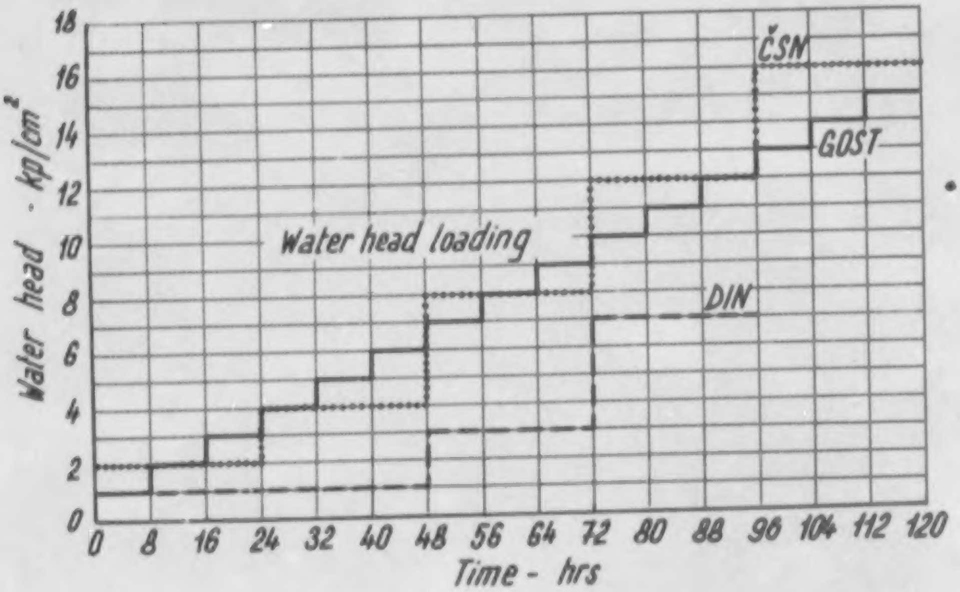

Fig. 4 Test for concrete permeability - GOST, DIN, ČSN

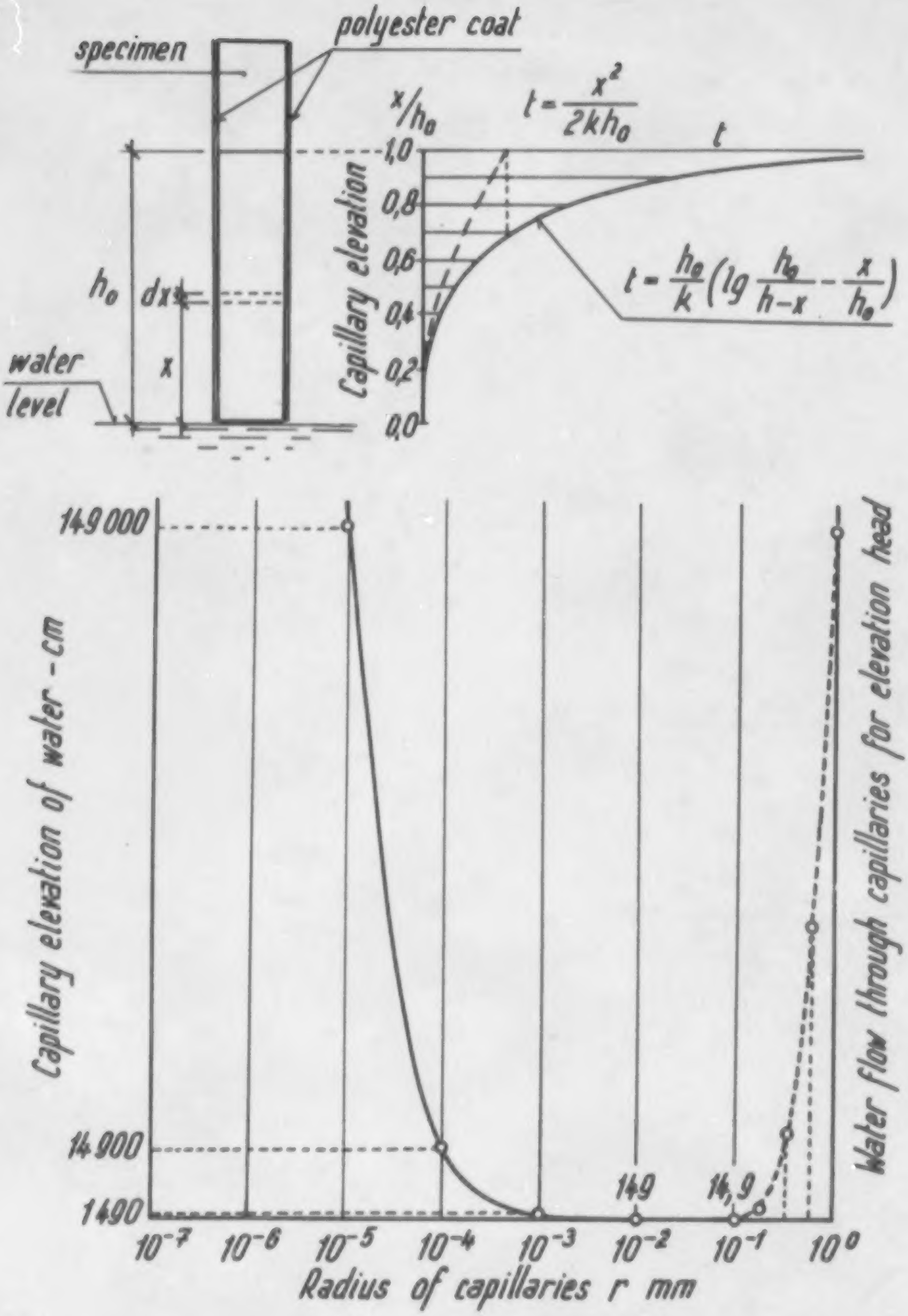

Fig. 5 Capillary elevation of water in poreous material

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Pore Properties in the Evaluation of Materials

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Many technologically-important materials are porous, and can be characterised by such pore parameters as porosity, specific surface and pore size distribution. The pore structure of such materials often plays a dominant role in controlling their useful properties. Attention is therefore drawn to some of the difficulties to be encountered in performance evaluation of such materials, when measured pore parameters have to be taken into account.

De nombreux matériaux techniquement importants sont poreux et peuvent être caractérisés par des paramètres de pores comme la porosité, la surface spécifique et la morphologie des pores. La structure des pores de tels matériaux joue souvent un rôle dominant pour le contrôle de leurs propriétés utiles. C'est pourquoi on attire l'attention sur certaines difficultés rencontrées dans l'évaluation de tels matériaux quand les mesures des paramètres de pore doivent être prises en considération.

Key words: Materials; performance evaluation; pore size distribution; porosity; specific surface.

1. Introduction

1.1 General remarks

According to the information given by the Advisory Group of RILEM to the meeting of the Permanent Committee held in Lund in 1970 concerning the activities and attitudes of RILEM towards application of the performance concept, the following statement can be made:

The main activities of RILEM are to promote the acceptance of the materials science approach in performance evaluation. In this respect, the A.G. considers that RILEM working groups should study the possibility of analyzing the connection between the factors affecting an object in use and the properties of the object needed to satisfy the demands of satisfactory service under given conditions.

This can be interpreted as an attempt to extend the work concerning the connection between performance characteristics and basic parameters of materials, products and constructions. At the Bucharest meeting of the Permanent Committee in 1969, a RILEM Committee concerned with the pore properties of materials was set up according to these principles. The pore structure is of importance in the evaluation of performance, as the porosity of a material affects most physical properties of the material; in fact, some properties are almost totally determined by the porosity. As the porosity in many cases is a characterising property of the material, the investigation of this property can give much information on many other properties. Therefore, it is very important to know

- how the pore properties may be investigated
- the reliability and limitations of these investigations
- the relations between the determined pore properties and other properties of the material.

In terms of the levels given in reference [1][1], the RILEM-PM Committee is working on the level of "internal structure" and using the results for the evaluation of a material or product. This evaluation may in many cases concern higher levels, as indicated in Table 5 of reference [1].

The committee has to list different pore porperties together with experimental methods which give information about these properties. It is of great importance to know the reliability and the advantages and disadvantages of the methods. The committee should collect earlier work where the porosity has been used to investigate some other properties of a material. It would also be of interest to list problems which could be investigated using porosity determinations.

The committee has started its work by making compilations of the quantities and symbols for the description of pore properties and reviewing methods for the determination of pore structure. Further, work on the use of pore structure determinations for the evaluation of materials has started.

1.2 The performance concept

It is generally accepted today that the central point of performance thinking is directed towards the fulfilment of the needs and demands of the intended use of a material. Beyond this, however, definitions differ. Some stress the importance of statements which are not tied to any particular system, product or material. Other definitions do not observe this distinction, but seek solutions which will optimize service in practice.

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[1] Figures in brackets indicate the literature references at end of this paper.

Although such definitions are not necessarily contradictory, it might be preferable, for the time being, to accept the performance concept simply as an idea and method, without attempting to adhere to any very strict definition. From the point of view of this paper, it is important to note that any structure, with its components and materials, has to fulfil its functions under the action of many factors which arise both from the use to which the structure is put, and from the environment in which it is used. In this context, a knowledge of the pore structure, and its relationship to the properties of a material, is of essential importance, and this is the aspect which we seek to stress here.

1.3. Pore properties in the evaluation of materials

The pore properties with which we are concerned are the fundamental parameters which describe the scale, extent and connectivity of the pore network in a porous material.

The relevant evaluation techniques are founded, in the first instance, on quantitative physical measurements of phenomena which may in turn be related by fundamental scientific principles to the appropriate pore properties. Since, however, the primary objective is to evaluate specific materials in relation to a given set of performance requirements, a further stage of interpretation is necessary. At this final level, we are concerned not so much with the fundamental pore properties themselves, but rather with their relationship with the performance characteristics of porous materials. This relationship may be established by both theoretical and empirical methods.

To give an example, we may use such methods of measurement as pycnometry, mercury penetration and gas adsorption to investigate the porosity, pore size distribution and specific surface of a sample of brick. The quantitative evaluation of the pore properties from these measurements follows scientific principles which are, in most cases, well-established. To complete the evaluation of the brick, however, we need to know how these pore properties are related to the strength and durability of the brick, its thermal and acoustic transmission characteristics, the ease with which rain-water will penetrate it, the capillary suction it will exert towards mortar joints and plaster renderings, and so on. These are the properties in whose terms the performance requirement will be specified.

2. Determination of pore structure

2.1 Pore structure parameters

The most elementary property of a porous medium is the volume of the pore space, which, when expressed as a fraction of the total volume of the material, is termed the porosity, ε :

$$\varepsilon = \frac{V_{pores}}{V_{total}}$$

This may be further subdivided into open porosity (that which is accessible from the outside) and closed porosity (such as totally enclosed gas bubbles).

Also of importance in many respects is the surface area exposed by the pores within unit volume (or mass) of the material, the specific surface, S.

The size of the pores is a most important property. In materials of common interest, pore sizes may range between nanometres and millimetres; the relative abundance of the various sizes may be expressed in the form of a pore size distribution.

Clearly, for pores with a given geometry, the three parameters porosity, specific surface and pore size (or its distribution) are inter-related. For example, for cylindrical pores of radius R:

$$\frac{SR}{\varepsilon} = 2$$

(with S on a unit volume basis).

For other geometries, the numerical factor takes other values, which are therefore an indication of pore shape.

In many applications, the total pore structure must be viewed as a three-dimensional network, and its interconnectivity, denoting the manner in which pores of various sizes are linked topologically, is a most important property (although it certainly cannot be expressed by a single parameter).

Finally, in many natural media, the pores may lie in a preferred direction, in which case the anisotropy of the pore structure is of importance.

2.2 Experimental methods for studying pore structure

Methods by which the structural parameters mentioned in 2.1 may be studied experimentally have been reviewed in detail by Gregg and Sing [2] and will also be the subject of a forthcoming publication of the RILEM/PM Committee. Here, we shall merely indicate the more important methods used in Table 1.

Table 1. Experimental methods and structural parameters.

Experimental method	Structural parameter
Pycnometry	Porosity
Gas adsorption Permeability	Specific surface
Mercury penetration Capillary condensation	Pore size distribution

Additionally, methods of direct visual (microscopic) examination of plane sections of a material can be used to obtain information on the pore structure.

Information on the remaining structural properties (pore shape, interconnectivity and anisotropy) can, in certain circumstances, be inferred from combinations of the measurements listed above.

3. External and internal factors

The paper on performance analysis submitted to this Symposium [2] describes an analyzing technique which is based upon the matching of certain "external factors" with various related "internal factors". The external factors reflect principally the different human requirements and the various influences of the environment. The internal factors are different properties of, and processes related to, the material. A listing of the various external factors is helpful in identifying the necessary material requirements. As we have already indicated, pore properties are highly relevant to many of the internal factors.

Table 2 gives an illustration of this. It is based upon the philosophy of external and internal factors as developed in reference [2]. The table contains a short list of external factors, with examples of the corresponding internal factors, which are further subdivided into processes and properties. Each of the properties listed as internal factors will be modified by the presence of pores in a material, and will therefore be dependent in some way on the pore structural parameters discussed above. Although the list is by no means complete, it shows very clearly the broad field in which knowledge of pore properties can be useful in the evaluation of materials. An expanded version of this list is being prepared for the quidance of the RILEM/PM Committee.

4. Discussion

In seeking to relate the basic structural parameters of a porous medium to its performance, two approaches are possible, which we may call theoretical and empirical. In the theoretical approach, we may, for example, attempt to calculate from basic mechanical principles what would be the strength of a solid having a given pore structure.

In the empirical approach, on the other hand, we would attempt to establish the form of the strength/porosity relationship from experimental data representative of a range of materials.

The theoretical method is one of great difficulty, sometimes because of imperfect understanding of the relevant theoretical principles, but always, additionally, because of the geometrical complexity of natural porous media. For this reason simplified models are frequently used to represent the real pore structure in more tractable terms. The same simplification is often introduced in the derivation of pore structural parameters from experimental measurements, and care should be taken to avoid the use of incompatible or contradictory models at these two levels.

An example of the type of difficulty encountered by the theoretical approach is seen in the problem of calculating, from fundamental principles of mechanics, the elastic moduli of porous materials. This can be done if it is assumed that the pores have some simple shape, such as spherical [3]. This assumption, which is necessary for the calculation of the stress distribution in the solid, must often be incorrect. The resulting equations have nevertheless received detailed experimental confirmation in at least one case [4]. Alternatively, it can be assumed that the porous solid comprises a sufficiently large number of small elements that its macroscopic behaviour approaches that of a continuous and homogeneous solid [5]. The detailed behaviour of individual elements is still unknown, however, except in terms of the pore geometry.

Table 2. Examples of cases where pore properties influence the performance.

External factors	Internal factors	
	Process	Property
Water and moisture	Water transfer	Capillarity Permeability to water
	Swelling Shrinking	
Heat	Heat transfer	Thermal transport coefficients
Frost	Freezing	Frost resistance
Fire	Ignition Spread of fire	Thermal stability Fire resistance
Air	Air leakage	Air permeability
Electricity		Electrical conductivity
Sound	Sound absorption Sound reflection Sound transmission	
Light	UV degradation	Chemical stability Optical properties
Chemicals	Corrosion	Resistance to chemicals
Impurities		Liability to get dirty Ease of cleaning
Human factors		
Psychological		Smoothness Texture

The empirical approach, whilst appearing to be simpler, also may encounter difficulties. These arise from the danger of attempting to describe a complex pore structure in terms of simple parameters. As explained above, this frequently involves the introduction of a model, which may fail to reflect, in its hypothetical parameters, some important features of the real system. For example, the strength of a porous medium may be disproportionately affected by the geometry of certain regions in the structure, such as the points of contact between particles, which are not taken into account in the model. These regions may be profoundly influenced by the method of sample preparation (e.g. sintering, cold compaction). This may be the reason why the empirical approach is in some cases unable to determine unequivocally whether the strength/porosity relationship is linear or exponential [6] and [7].

The essential objective of both approaches is predictive: to enable us to extrapolate from our experience of known materials and conditions. In addition, the theoretical approach seeks to gain some understanding of the properties of porous materials. There is much progress to be made in both fields.

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The Definition of a Low Intensity Fire*

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A reproducible fire of low intensity may be used for the realistic performance evaluation of interior finish materials and of structural building elements. The burning behavior of furniture and the contents of wastebaskets are defined in terms of the rates of heat release, heat transfer to the surrounding walls, and heat losses by radiation and convection. Experimental measurements of temperature and radiation levels within a room are summarized for a variety of combustible contents and mass loadings. Selected low intensity fires have been examined for repeatability and for potential use in evaluating fire safe requirements for interior finish materials in terms of the spread of flame, generation of smoke and overall fire growth pattern.

Un incendie de basse intensité reproductible peut être utilisé pour l'évaluation réaliste de la performance des matériaux de finition intérieure. La façon de brûler de l'ameublement et du contenu de corbeilles à papier et de barils de rebuts peut être définie en termes d'équilibre d'énergie, impliquant la vitesse de libération de chaleur, le transfert de la chaleur aux murs d'entourage et les pertes de chaleur par radiation et convection. On résume, pour divers contenus combustibles et degrés d'encombrement, les mesures expérimentales de température et les niveaux de radiation à l'intérieur d'une pièce. Des incendies de basse intensité sélectionnés ont été examinés pour leur possibilité de reproduction et utilisés pour évaluer les exigences de tenue au feu des matériaux de finition intérieure en termes d'expansion des flammes, de génération de fumée et de types d'expansion générale du feu.

Key words: Buildings; calorimetry; combustibility; fire intensity; flame spread; furnishings; heat release; thermal radiation; wastebaskets.

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1. Introduction

Fires in buildings generally start small and grow in size. The fire which begins in a wastebasket or piece of furniture may eventually involve all other combustible items in an entire room or floor. The burning characteristics of a fully involved room fire are generally represented by the temperature time curve employed in the standard fire endurance test (ASTM E119). This exposure is used to evaluate the ability of building components to contain the further advance of fire and to remain structurally stable. However, the typical small or initiating fire has not been adequately delineated or standardized.

There are two main reasons for studying typical small fires which may or may not grow to room size. First, there is a need for a realistic way to evaluate the ignitability, flame spread, and smoke generation properties of interior finish materials used on walls, ceilings, and floors. Second, there is a need to determine the effect of a relatively small localized fire on the load-bearing capacity of structural components, such as lightweight (sandwich) panels and unprotected metal columns or frames, as well as air-supported structures, etc. Investigation of both these effects contribute to more meaningful performance evaluation of materials and constructions under conditions at the initiation of a fire.

The immediate objective of this study is to define the burning behavior of minor (incidental or low-intensity) fires, such as those which occur in metal and plastic wastepaper baskets and trash cans or in upholstered furniture. The fire characteristics considered are the rate of burning (weight loss) and heat release of the combustible, the temperatures of the flames and hot gases produced, and the energy transferred by radiation and convection to nearby surfaces.

2. Experimental Details

2.1 Test Room

Experiments were performed in a fire test room measuring 2.9m (9 1/2 feet) by 3.2m (10 1/2 feet) by 2.4m (8 feet) high. One (open) door 1.3m (4 feet, 2 inches) by 2.3m (7 feet, 9 inches) high was located in one of the smaller compartment walls. The whole test compartment was situated inside a large building, assuring draft-free conditions. Three compartment walls and the ceiling were concrete, the fourth wall was 16mm (5/8 inch) gypsum wallboard sprayed with an insulating vermiculite/gypsum plaster.

2.2 Instrumentation

Four copper disc calorimeters were mounted in an asbestos board holder which was placed either at the rim of the wastebasket or at the top edge of the upholstered chair back. These calorimeters measured the maximum rates of total heat flux and were in direct contact with the flame during the test. The 25mm (1 inch) diameter by 3mm (1/8 inch) thick discs had a blackened front surface and a thermocouple attached at its center. The rate of temperature rise of the disc is directly related to the incident heat flux. A copper pan calorimeter, which had two attached thermocouples to measure its rate of temperature rise, was constructed for determing the rate of heat conducted downward to the floor underneath the wastebasket. A copper disc calorimeter was placed on the floor beneath the upholstered chair.

Thermal heat flow meters were installed on the wall surfaces to measure the magnitudes of heat flux through the walls. Radiometers facing the flames were employed to determine either the radiant flux or the total flux density, a combination of convection and radiation. Temperatures of the plume gas along the flame centerline above the wastebasket or chair and the hot gases at various locations within the compartment were measured by bare-beaded chromel-alumel thermocouples made from 0.5mm (0.020 inch) diameter wires. Additional thermocouples were separately fixed firmly to the outside lateral wall of the wastebasket for measuring its surface temperatures during the fire.

A load cell was used for continuously recording the rate of weight loss of the burning combustibles.

2.3 Test Specimens

Wastebaskets of several sizes were studied. Of the six types of galvanized or painted steel trash baskets used, five were of round cross-section, one was square. There was one type of large plastic wastebasket. The combustibles were plasticized paper milk cartons, paper tissue, carbon paper, paper towels, and kraft wrapping paper.

The chairs were upholstered in several types of fabrics and were padded either with cotton batting (overstuffed) or plastic foam cushioning. A typical test of an upholstered chair is illustrated in Figure 1.

Fire load density was defined as the weight of combustible per unit bottom area of the wastebasket or chair. Table 1 summarizes the main variables for each test.

3. Test Procedure

For each wastebasket test, the wastebasket was filled to maximum capacity (without compression) with the preweighed combustible contents. The basket was then placed on the copper pan calorimeter. Ignition was started by momentarily touching an open flame to the contents at the top of the wastebasket, at which time all recording instruments were turned on simultaneously.

For the upholstered chair tests, ignition was effected by using two methenamine "timed burning" tablets placed at the juncture of the seat cushion and the chair back. The development and burning behavior of the experimental fire was recorded during each test.

4. Test Results

4.1 Wastebaskets

The rate of burning is the measured rate of weight loss expressed in g/min, or percent of original weight per minute. The fuel consumption rate, duration of burning, plume gas temperature and the rate of heat transfer at the peak of the fire are presented in Table 1 for each test.

In the wastebasket tests there was a fairly rapid weight loss during the early stages followed by a gradual decrease in the rate. This represents the gradual change from burning with unlimited combustion air at the top of the fuel bed to a condition of partially restricted air flow as the active burning stage moved lower into the basket. It was established from replicate tests that the rate of burning of wastebasket fires was fairly repeatable. Of the combustibles tested, plasticized paper milk cartons had the highest rate of burning.

The effect of fire load density on the average burning rate, expressed in percent/min., is shown in Figure 2. This graph includes data from tests with large and small wastebaskets including some tests on small plastic wastebaskets not listed in Table I. The average relation for all steel wastebasket test data can be represented by RD=5, where R=rate of burning, in percent/min and D=fire load density, in g/cm^2. Over the range studied, the rate of burning, R' (g/min) was found to be generally proportional to the bottom area of the wastebasket, A, and independent of the total combustible load; thus R'=0.05A.

In these tests, the maximum measured temperatures of the hot gases within the flame plume above the wastebasket varied from 700 to 1050 C (1292 to 1922 F) with an average of approximately 860 C (1580 F). The temperature of air in the vicinity of the compartment ceiling generally ranged from 100 to 400 C (212 to 752 F) at the peak of fires for all tests.

From the copper disc calorimeters, the maximum total heat transfer from the flame to a surface tangent to the rim of the container varied from 0.6 to 5.3 W/cm^2 (0.5 to 4.7 Btu/ft^2 sec) with an average of about 2.3 W/cm^2 (2.0 Btu/ft^2 sec). This heat transfer rate, from flame gas to solid surface through convection and radiation, is quite capable of producing the ignition of adjacent combustible materials. The peak flux measured was at a height of 22.9cm (9 inches) above the wastebasket and occurred about 2 minutes after ignition for most tests. The peak heat flux levels were maintained for 1 to 3 minutes.

The experimental results indicate that the magnitude of peak heat flux close to the flame plume is generally proportional to the rate of fuel consumption. (For the milk cartons, the range in measured fuel consumption rate was very limited.) An increase in fuel burning rate would undoubtedly produce an increase in the flow of hot gases past the adjacent surface, thereby yielding a higher rate of heat transfer to the surface through forced convection. The milk cartons gave the highest incident flux values and the paper tissues the least.

The spatial distribution of heat flux was obtained from readings of windowless radiometers mounted on stands and placed parallel to the wastebasket centerline at various distances from the wastebasket and at an elevation of 10cm (4 inches) above the top edge of the container. It was noted that at a short distance, 5 to 15cm (2 to 6 inches) away from the wastebasket, radiation became the dominant mode of energy transport, comprising approximately 70 percent of the total energy.

Measurements were made of the maximum rate of heat transmitted downward to the floor underneath the container, the maximum radiant flux emitted, and peak temperature attained by the container wall during each test. The plastic container usually reached a higher temperature, ranging from 600 to 800 C (1112 to 1472 F) at its lateral surface compared with the measured temperature for a metal container of from 160 to 500 C (212 to 932 F). The data indicate that the heat flux conducted to the floor and the burning rate of combustibles inside a plastic wastebasket are significantly higher that those from a fire in a metal container. These results are expected since a considerable amount of heat was liberated from the burning of the plastic container itself.

For both the wastebasket and upholstered chair fires, it was estimated that 1 percent of the available heat energy was lost through the open door by radiation and 2 percent by convection.

4.2 Chairs

In the upholstered chair tests, the data and burning behavior were more variable since the chairs were all of different weights and constructions and had undergone varying degrees of wear and usage. Four of the five chairs burned completely in times ranging from 41 to 86 minutes. Excluding the one chair, which only burned partially (due to the upholstery fabric), the maximum measured temperatures of the hot gases within the flame plume varied from 460 to 1080 C (860 to 1976 F), with an average of approximately 800 C (1472 F). The maximum air temperature near the ceiling ranged from 170 to 265 C (338 to 509 F) and the average temperature of air in the fire compartment generally increased 50 to 100 degrees C (90 to 180 degrees F). The maximum total heat flux, which was measured with the copper disc calorimeters mounted above and along the chairback, was found to range from 0.3 to 4.4 W/cm^2 (0.26 to 3.9 Btu/ft^2 sec) with a mean value of 1.7 W/cm^2 (1.5 Btu/ft^2 sec). Tests with upholstered furniture are continuing.

Typical curves of plume gas temperature versus time for fires involving a single upholstered chair and a wastebasket are shown in Figure 3. The ASTM E119 Standard temperature-time curve was also plotted in the same figure for comparison. It can be seen that the temperature of the hot gases within the flame plume increased rapidly during the early stage of a wastebasket fire whereas the temperature rise from the upholstered chair fire was limited during the extended period of gradual involvement. Both minor fires were localized and had a relatively short duration of peak temperature; the temperature in the standard ASTM E119 test is applied to the entire surface of a wall or ceiling and increases continuously.

5. Discussion

An incidental or low-intensity fire, as already defined, is of limited size, duration, and energy content. However, a low-intensity fire may cause ignition of adjacent combustibles or furnishings, or the combustible interior finish materials on walls, ceiling or floor. The occurrence of critical secondary ignitions depends upon the intensity and duration of the incidental fire, and the properties and geometrical arrangement of the subsequently exposed surfaces.

A comparison between the severity of the standard fire endurance test exposure (for the corresponding burning period) and an incidental fire involving a single large wastebasket or upholstered chair is indicated in Table II.

An incidental fire started locally by a match undergoes an initial stage in which the fire spreads laterally, then a stage of rapid (maximum) burning, followed by a deceleration stage generally associated with glowing and little or no flaming. The duration of such a fire is short and somewhat indefinite. A fully involved fire on the other hand represents the burning of fuel for a prolonged period.

6. Summary and Conclusions

Experimental and analytical studies are continuing in an effort to define the burning characteristics of minor (incidental or low-intensity) fires. These tests are providing useful information for the performance evaluation of materials and constructions when exposed to fire. On the basis of data so far assembled, the following tentative conclusions may be drawn:

1. Incidental fires may approach or exceed the fully involved fire represented by ASTM Standard E119 in terms of peak levels of temperature and heat flux to adjacent surfaces. However, these peak levels are localized and exist for only short periods of time. Over the local area involved, the peak energy output per unit of floor area of an incidental fire may be 80 to 100 percent of the average for a fully involved fire.

2. A large wastebasket fire during a 20 minute burning period may generate up to 2 percent of the total energy and 5 percent of the maximum rate of energy released compared to heat from the contents of a room fully involved in fire.

3. An upholstered chair fire during a 60 minute burning period may generate up to 4 percent of the total energy and 15 percent of the maximum rate of energy release compared to a fully involved room fire.

TABLE I

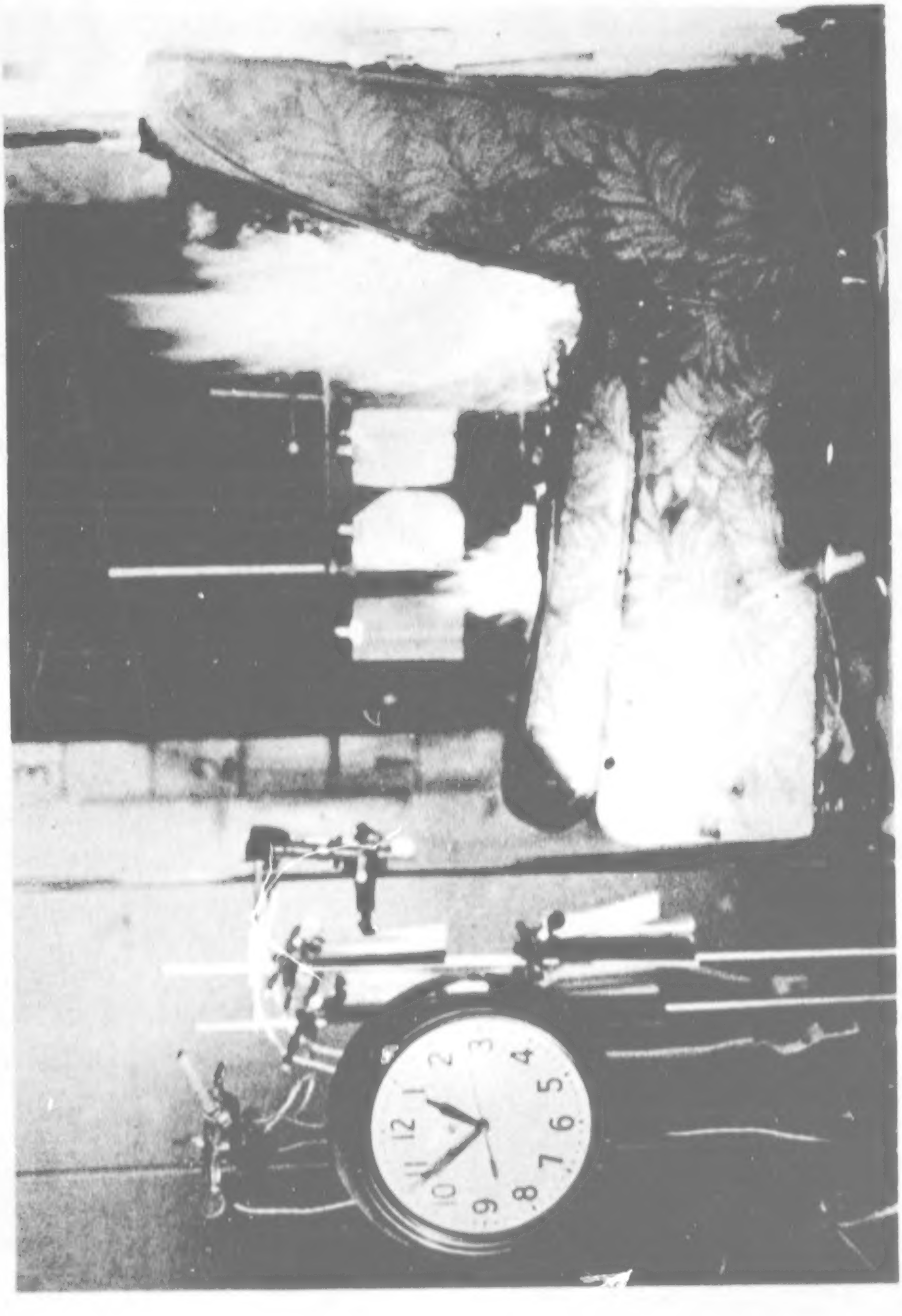
TEST PARAMETERS AND RESULTS

Wastebasket	Type	Measured Capacity Gal	Measured Capacity Liters	Combustible Type	Weight g	Fire Load Density g/cm²	Maximum Fuel Burning Rate (g/min)	Duration Time (min)	Maximum Plume Temperature (°C)	Maximum Total Heat Flux at Flame Edge (W/cm²)
Wastebaskets										
Steel	A	18.9	71.5	Paper Tissue	1367	1.60	82	24.5	805	0.67
Steel	A	18.9	71.5	Paper Tissue	1304	1.52	64	17.4	705	0.58
Steel	A	18.9	71.5	Kraft Wrapping Paper	2568	3.00	277	26.0	996	2.99
Steel	B	7.04	26.6	Kraft Wrapping Paper	1157	1.63	242	15.2	1001	3.83
Steel	B	7.04	26.6	Milk Cartons	723	1.02	161	12.5	886	2.46
Steel	A	18.9	71.5	Milk Cartons	1663	1.94	192	23.2	1015	1.92
Steel	C	9.86	37.3	Milk Cartons	907	1.15	173	15.2	861	4.97
Steel	D	4.74	17.9	Milk Cartons	595	1.07	140	13.5	819	4.19
Steel	E	20.4	77.2	Milk Cartons	1778	1.61	308	21.2	936	2.25
Steel	F	30.7	116.0	Kraft Paper Towel	1285	0.783	238	16.9	831	1.35
Steel	E	20.4	77.2	Kraft Paper Towel	853	0.774	216	13.0	743	1.04
Steel	A	18.9	71.5	Kraft Paper Towel	1090	1.27	236	19.8	827	2.63
Steel	C	9.86	37.3	Kraft Wrapping Paper	1469	1.86	308	18.6	896	3.62
Steel	C	9.86	37.3	Kraft Paper Towel	574	0.725	168	18.2	787	1.62
Steel	D	4.74	17.9	Kraft Paper Towel	200	0.358	105	5.7	714	1.13
Steel	F	30.7	116.0	Kraft Wrapping Paper	3490	2.13	631	20.6	986	3.18
Plastic	G	31.7	120.0	Milk Cartons	2799	1.80	570	9.3	966	2.57
Steel	F	30.7	116.0	Milk Cartons	2822	1.72	390	26.8	1056	3.09
Plastic	G	31.7	120.0	Carbon Paper with Onion Skin	865	0.557	393	17.4	818	1.31
Steel	F	30.7	116.0	Carbon Paper with Onion Skin	865	0.527	259	4.9	781	1.08
Steel	B	7.04	26.6	Kraft Wrapping Paper	619	0.870	144	15.7	703	2.15
Steel	F	30.7	116.0	Paper Tissue	1702	1.04	265	16.0	808	0.84
Steel	A	18.9	71.5	Kraft Paper Towel	790	0.923	166	26.0	797	0.75
Plastic	G	31.7	120.0	Paper Tissue	1718	1.11		22.0	894	1.41
Plastic	G	31.7	120.0	Milk Cartons	2794	1.80	584	16.1	934	3.83
Steel	F	30.7	116.0	Milk Cartons	2749	1.67	420	25.3	855	2.29
Steel	F	30.7	116.0	Milk Cartons	2780	1.69	465	27.6	844	5.26
Steel	E	20.4	77.2	Milk Cartons	1795	1.63	278	24.6	860	3.10
Steel	A	18.9	71.5	Kraft Paper Towel	790	0.923	166	20.1	819	1.53
Upholstered Chairs										
Upholstery Fabric				**Padding**						
Cotton				Cotton	9640	2.60	230	83	1066	1.09
Rayon/Nylon				Cotton	20900	3.54	920	66	463	0.99
Nylon				Cotton/Horse Hair	12800	3.23	51*	56	100	0.45
Cotton				Cotton	21300	4.44	1310	86	568	0.33
Rayon				Polyurethane Foam	22900	3.70	1100	41	709	4.42

* The chair was partially consumed.

TABLE II COMPARISON OF INCIDENTAL FIRES AND STANDARD FIRE ENDURANCE TEST

	Standard Fire Endurance Test - ASTM E119		Incidental Fires			
			Large Wastebasket		Upholstered Chair	
Duration of burning period, min	20	60	20	(same)	60	(same)
Heat generated, total, Kcal	6.3×10^5	2×10^6	14,000	(2%)	83,000	(4%)
Heat generated, max rate W	2.2×10^6		1.1×10^5	(5%)	3.2×10^5	(15%)
Max. temperature, plume °C	} 795	} 927	860		800	
Max. temperature ceiling °C			300		350	
Incident heat flux, max W/cm^2	7	12	4	(50%)	4	(30%)
Floor area involved, cm^2	3×10^5		6×10^3	(2%)	1.5×10^4	(5%)
Fire load, g/cm^2	1.6 (equivalent distributed)	4.8	2 (local)	(>100%)	3.4 (local)	(70%)



12
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11

Fig. 1 Active burning of "overstuffed" chair.

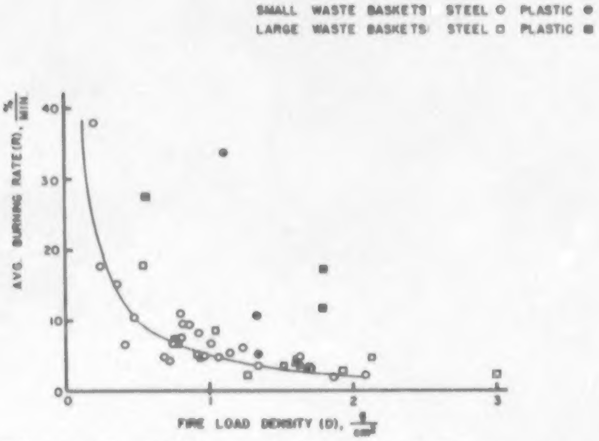

Figure 2 Effect of Fire Load Density on Burning Rate

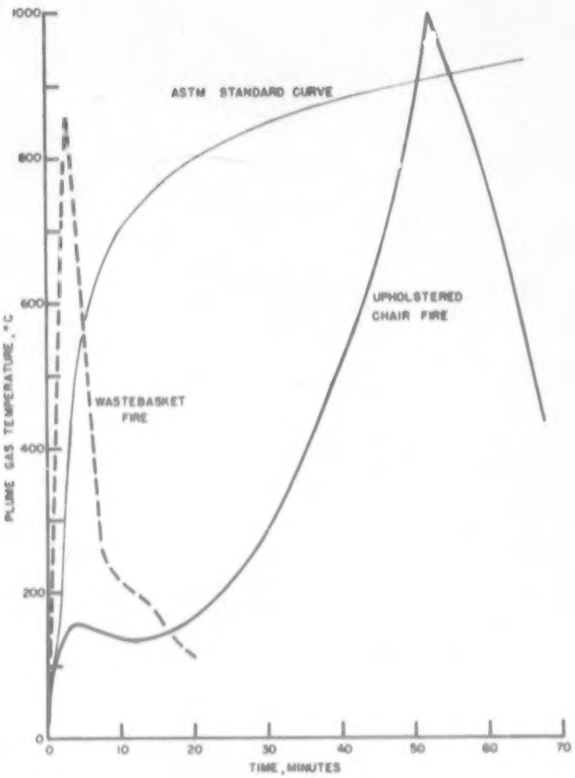

Figure 3 A Comparison of Time-Temperature Curves

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The Interaction Between Mortar and Masonry Units as a Basis for Standards for Masonry Mortars

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The paper describes a draft standard for masonry mortars which is based on the application of the performance concept on the "product"(material) level. The approach is based upon a statement that the solutions have to give optimal service, under the action of the external factors. In this case, the object of the analysis is fresh mortar. The most important external factor affecting the mortar is the suction exerted by the masonry units. The removal or non-removal of water has deciding effects on the mortar joint as a whole. Therefore, the properties of the mortar have to be matched to the properties of the unit. The evaluation of the mortar is based on the interaction of the mortar and the masonry unit. Testing methods and the general background of the evaluation are described. The final evaluation lies in the hands of an expert panel.

La communication décrit un projet de norme pour les mortiers de maçonnerie, norme fondée sur l'application du concept de performance au niveau du "produit"(matériau). On part du principe que les solutions doivent opérer de façon pour le moins satisfaisante sous l'action des facteurs externes. Dans ce cas, l'objet de l'analyse est le mortier frais. Le facteur externe le plus important qui affecte le mortier est l'absorption de vapeur d'eau par les unités de maçonnerie. Le déplacement ou l'absence de déplacement d'eau a des effets déterminants sur le joint de mortier in toto. C'est pourquoi les propriétés du mortier doivent être assorties aux propriétés de l'unité. L'évaluation du mortier est fondée sur l'interaction du mortier et de l'unité de maçonnerie. Les méthodes d'essais et la documentation générale de l'évaluation sont décrites. L'évaluation finale est confiée à un comité d'experts.

Key words: Fresh mortar; interaction between masonry mortars and units; mortar evaluation; mortar standard; masonry mortar; suction of masonry unit; winter masonry.

1. Introduction

In the paper on performance analysis [1][1] submitted to this Symposium, it is stated that the performance concept can be applied to different levels of building. The approach in that paper is based upon a statement that the solutions wanted have to give us an optimal service in the conditions of use, e.g., under the action of different external factors.

Building mortars fall within the "product" level in the scheme (see also Table 1). "Building elements" are made with the aid of mortars and masonry units, and this level has also to be analysed. As the building elements form "parts of buildings" (spaces), technical requirements have to be taken from this level, too. At the same time the performance of a mortar is dependent upon the lower, more fundamental levels.

According to the results of the Delphi-study [2] performed within the RILEM committee on "Performances of mortars and renderings", the most important level for the evaluation is "product combination (Table 1), e.g., the interaction between mortars and masonry units. This result is based on the estimation of the performance of fresh mortars. The suction of the masonry unit is the most important external factor affecting the mortar. As most masonry mortars contain hydraulic binders, the removal or non-removal of water has decided effects on the mortar joint as a whole and also upon the bond. Therefore, the properties of the mortar have to be matched to the properties of the masonry units, and the evaluation has to be based upon the interaction between the mortar and the masonry unit. The results of the Delphi-study are in agreement with this opinion.

The conventional approach where units meeting specification requirements are combined with a mortar of a specified composition cannot always be the correct way of solving the problems. Evaluation techniques have to be developed which give more freedom and do not work against innovative approaches.

2. Draft standard for masonry mortars

2.1. General

The discussion below concerns a proposal for a new Finnish standard for masonry mortars which is in preparation at the time of writing (December, 1971). The draft is based upon work done within the Scandinavian Mortar Committee.

At the time being, there is no possibility of writing mortar standards which are wholly based upon a performance approach. Therefore, the proposal is partly conventional, partly performance based.

The task of the masonry mortar is to bind the building stones together in order to form a firm and durable structure. Also aesthetic and economic requirements must be met.

According to research and experience, the masonry requirements can in general be reached when mortars meeting specification requirements are used. For conventional use certain lime, lime-cement and cement mortars are listed in the "conventional" part of the standard.

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[1] Figures in brackets indicate the literature references at end of this paper.

The performance-oriented part of the standard is built around the fact stated above that the suction of masonry units is the most important external factor which affects the fresh mortar, and especially the properties of the hardened mortar. The suction varies depending on the water absorption of the unit, its rate and capillary suction force. Water removal by the masonry unit and its consequences affect the strength of the mortar bed as a whole and the properties of the boundary between the masonry unit and the mortar. Shrinkage and swelling of the mortar and the masonry unit due to moisture change, and thermal movements also affect the quality of the joint.

The aim of the standard is to give practical directives for the selection, preparation and use of mortars in central mixing facilities and at building sites. The performance-oriented part of the standard is believed to promote development and innovations.

2.2. Requirements and tests

The requirements on materials and products concern ingredients, and fresh and hardened mortars. Table 2 lists the different items on mortars which are considered in the standard. One part of the mortar requirements and tests concerns the fresh mortar, some need tests where the mortar is investigated together with masonry units (bricks). In this case, particular masonry units may be used or, for general purpose, the mortar may be tested together with the following masonry units:

1. Masonry unit with a small initial rate of absorption (I.R.A.) and a low suction power - clay brick of the I.R.A. class 10.
2. Masonry unit with a high I.R.A. and a low suction power - clay brick of the I.R.A. class 40.
3. Masonry unit with a low I.R.A. and a high suction power - sand-lime brick of the I.R.A. class 10.

The I.R.A. classes are according to proposals for Finnish standards for bricks and sand-lime bricks. The I.R.A. is expressed in grams/sq.dm/min.

Table 3 gives an example on the results obtained by this kind of tests. As can be seen, the same mortar may become twice as strong when used in contact with different commercial products of the same type of masonry units.

It has to be kept in mind that many of the testing methods are in a stage of development, and it is often necessary to make the tests on a relative basis, which means that one has to compare the results with values obtained with "generally accepted" older mortars. There are no possibilities to give definitive values for the results of all tests.

2.3. Winter masonry

Winter masonry forms a special example on the effects of the water content of the mortar during hardening. The low temperature is another factor affecting the mortar. The frost damage is dependent upon the amount of water in the mortar during freezing. As the water removal from the mortar is of importance for masonry work in cold weather, the interaction between the building stones in question and the mortar have to be known before the working operations are started.

The results obtained in the Scandinavian countries [3] are in agreement that winter masonry work can be conducted if at the time of freezing

- the water content of the mortar has been lowered enough by the suction of bricks, or
- the mortar has prehardened enough before freezing.

The third alternative - the mortar freezes immediately - is not generally recommended, as it might lead to excessive settling upon thawing.

The draft standard requires that masonry units can be accepted for winter masonry if the water content of the mortar is diminished by suction of the masonry unit before freezing to 6 % by weight.

2.4. Evaluation and approval

The approval of a certain mortar, or a mortar/masonry unit combination has to be applied for by presenting results of testing to a committee on masonry constructions. This committee has to make decisions concerning the approval of the mortar.

The evaluation of the mortar is based upon determination of its workability properties and performance-based testing of the mortar. The interaction between the mortar and masonry units is regarded as the decisive factor. For instance, it has to be proved by tests that a satisfactory bond and strength is achieved when the mortar is used with a known masonry unit.

Besides the testing methods given in the standard, the committee may also accept results obtained with other methods, if they can be proved to give reliable results from the point of view of the performance of the construction.

For these reasons, it may be concluded that the final evaluation of a mortar is based upon "judgment by experts".

In this case, the main factor affecting the performance of the mortar, is the low temperature. If the water content of the mortar is low enough, or the strength of the mortar is high enough, or the water freezes when the mortar is structureless, damages due to the frost may be avoided.

3. Conclusions

The suction of the masonry units exert a decisive influence upon the fresh mortar. The properties of the mortar/building stone combination and, hence, of the masonry construction are determined by this interaction. Mortar and masonry standards may be built up according to this way of reasoning.

Table 3. The tensile strength of lime-cement mortars hardened between two types of sand-lime bricks.

Lime-cement mortar Lime/cement/sand by weight		Tensile strength N cm^{-2} (psi) Sand-lime brick A	 B	 Ratio B/A
LC	20/80/400	70 (101.5)	120 (174)	1.7
LC	35/65/500	30 (43.5)	60 (87)	2
LC	50/50/575	10 (14.5)	20 (29)	2

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Table 1. The performance evaluation of masonry mortars may be based upon research performed at different levels. In the Delphi-study [2] the answers have been numbered from 7 to 1 with 7 = the most important and 1 = the least important level. The means are given in the table.

1.0	Building
2.0	Part of building
4.0	Building element (e.g., wall)
6.8	Product combination (e.g., masonry unit/mortar-combination)
5.8	Product (e.g., masonry unit, mortar)
4.5	Material (e.g., cement, lime, sand, admixtures)
3.7	Internal structure (e.g., chemical composition, pore properties, cohesion)

Table 2. Properties and tests of fresh and hardened mortars.

- Fresh mortar
  - Water separation
  - Stiffness
  - Stiffening
  - Workability
  - Air content
  - Water removal by building units
    - Stiffening under suction
    - Instant adhesion

- Hardened mortar
  - Strength of mortar prisms
  - Strength of mortar prisms prepared between building units
  - Strength of mortar bed
  - Strength of 1/2 x 1/2-stone columns
  - Bond, tensile
  - Bond, shear
  - Water absorption
  - Pore size distribution
  - Efflorescence
  - Frost resistance

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A Performance Evaluation of Thin Bed Adhesive Mortar in Concrete Masonry Construction

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The rising cost of labor in recent years has prompted the concrete block industry to develop new methods of building walls. Of the many techniques created, the concept of gluing together dimensionally accurate concrete units has been the most successful. For the past 10 years, projects have been built with an adhesive mortar and block, providing an arena for demonstrating the performance characteristics of this concept. Both physical properties from ASTM test methods and economics from case histories prove that this concept is acceptable and practical.

L'augmentation croissante des frais de main d'oeuvre dans les dernières années a poussé l'industrie des blocs de béton à développer de nouvelles méthodes de construction de murs. Entre les nombreuses techniques créées, le principe du collage d'unités de béton de dimensions exactes s'est révélé le plus fructueux. Ces 10 dernières années, des projets de construction ont été réalisés avec du mortier adhésif et des blocs de marque "THREADLINE", ce qui a procuré un champ de démonstration des caractéristiques de performance du procédé. Les propriétés physiques évaluées par les méthodes d'essai ASTM, de même que l'enseignement économique fourni par des cas réels, prouvent que cette technique est acceptable et pratique.

Key words: Adhesives; concrete masonry; cost performance; ground concrete block; mortar.

1. Introduction

The method of building walls with masonry has been relatively unchanged since its inception hundreds of years ago. Modest improvements have been developed over the years, but the basic tools of trowel, level and hammer remain. The mason of today lays block as his grandfather did years ago. The block manufacturing process has improved dramatically in the past 50-60 years, so much that the cost of a block has been relatively stable through the years. Labor costs, on the other hand, have increased substantially, a combination of the old method with today's labor rates. Figure 1 illustrates this comparison of labor to materials costs over the past sixteen years.

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The dramatic increase of labor costs in this time period is convincing evidence that the place to reduce finished wall costs is in labor rather than materials. Since the mason's wages cannot be reduced, the concrete masonry industry has been searching for ways to make him more efficient, i.e., ways and means whereby he can lay more block per day without any additional work effort. With lower-performance, lower-cost materials of construction continually gaining markets that were once concrete block, the entire masonry industry is searching for improved ways to build their walls. How to produce the same attractive, durable, fire-resistant walls at a competitive price in today's construction market is a constant challenge.

2. Discussion

It is a recognized fact that the greater portion of a mason's block laying time is spent leveling the block in the bed of mortar. As they are normally manufactured, concrete block are not precise in their height dimension. The bottom and four sides of the unit are smooth, molded surfaces, but the top is relatively rough and uneven. Thus, when laid in a wall, the thick mortar joint is required to compensate for the manufacture irregularities. If the top and bottom surfaces (bed joint surfaces) could be made smooth and parallel, the mortar joint thickness could be reduced, and the mason could simply lay one block directly on top of the other and eliminate much of his time consuming, leveling operations.

Many solutions to this have been developed, but the one that provides the most versatility at the lowest cost, with no sacrifice in properties, is the thin bed adhesive mortar concept. By using a concrete masonry unit that has its top and bottom surface ground smooth and parallel in a post-manufacturing grinding operation, the mason can simply lay one block on top the other and build a plumb wall. By combining this ground block with a high bond adhesive mortar, the output of the mason can be increased at least two-fold, and result in a finished wall cost that is competitive with that of other lower performance materials. Figures 2 and 3 show how the adhesive mortar is applied.

A tradition-bound industry requires that a new concept be proven to meet the requirements established by decades of experience and testing. Time, as well as the laboratory, has proven the capabilities of conventional sand and cement mortars. For such a radical technique as gluing to be accepted, performance must be proven. Both the physical as well as the economic properties must be established.

In 1963, The Dow Chemical Company began work on an adhesive mortar,[2] a four-component product which consists of latex, portland cement, and epoxy. When properly mixed and applied to the ground surfaces of a block, a mortar joint in the wall less than one sixteenth of an inch thick results. Although it is relatively thin, this joint is stronger than the block. Beginning with small scale specimens and then full scale walls, data were accumulated which demonstrated that high strength walls could, indeed, be built with this adhesive. The results of this testing will be discussed later.

The physical performance criteria for concrete masonry and conventional mortar have been well established. Testing is constantly being conducted in various laboratories across the country to gain more insight into the capabilities of masonry and mortar. These tests, then, become the guide-lines for codes regulating the construction of walls with these materials. They also are the criteria for an adhesive mortar evaluation.

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[2] THREADLINE®, all adhesive mortar data reported in this paper were obtained with this product.

In tables 1, 2, and 3 are listed ASTM test results of walls and small scale specimens built with conventional sand-cement mortar. These data are a compilation of several sources spanning ten years of testing. (The sources of data and description of mortar types are given at the end of this report.) It was felt that such a summary would be a meaningful and representative sampling of work conducted on these mortars.

The compressive prism test data shown on table 2 should be clarified. This is a method recommended by the National Concrete Masonry Association as a test procedure for evaluating block and mortar for load-bearing construction. Based on a history of testing, it is now possible to correlate prism strength to wall strength, thus permitting the design of walls to be based on actual test data, rather than the arbitrary values frequently employed in the past. This method is now accepted by several national codes and is part of NCMA's recent specification on load-bearing concrete masonry. [1][3]

Similar tests were conducted on concrete masonry specimens built with the adhesive mortar and are reported in tables 4 through 6. Wall tests as well as similar small scale specimens were evaluated and reported.

Most of the strength data are reported in terms of gross area, i.e., the load at failure divided by the over-all cross-sectional area of the block or masonry. In the case of bond tests, however, the strengths are reported in terms of net area, i.e., area of contact with the mortar.

By precedence, then, the sand-cement mortar data become the criterion with which a new mortar system must compare. The variations of strength in the data for conventional mortars (tables 1, 2, and 3) are results of the various mortar types and other parameters, which are not applicable to this study. In essence, a representative range of values was sought, in order to achieve a comprehensive comparison to the adhesive mortar.

Summaries of these test data are given in tables 7 and 8, for wall tests and small scale specimen tests, respectively. Here, the values are presented in bar graphs to visualize the comparison of the sand-cement and adhesive mortars. Note that the adhesive mortar is consistently comparable to, or exceeds the values of the sand-cement mortar specimens. It should also be emphasized that the failures in the adhesive mortar tests were always in the masonry units rather than the mortar. This suggests a possibility of future designs which will fully utilize the strength of the masonry unit and not be limited by the mortar.

Having established the physical performance of the new material let's look at the overall economics of walls built with it. Since labor savings are the significant factor in the use of this system, a close examination of the masons' performance is critical to its acceptance. Without the proper cost effectiveness, adhesive mortar could have easily become another laboratory curiosity.

One of the first buildings constructed with this system was closely monitored during construction so the actual costs could be compared to an estimated cost in conventional mortar. This project was built in the winter of 1965 and is detailed in table 9. Even though the labor rates then were considerably lower than today, a significant savings of over 17% was realized. Although the material costs of the adhesive system were 14% higher than conventional, this was offset by the large reduction in labor costs. Of course, increased labor rates since that time would change the economic picture even more in favor of this adhesive mortar system.

Since then, many more projects using this mortar have been built, substantiating the fact that masons can and will lay more blocks, given the proper materials, thus reducing the overall finished wall costs. Rather than detail all these projects, several are listed in table 10 showing actual mason productivity versus the normal rate for the same type of wall construction in each respective area.

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[3] Figures in brackets indicate the literature references at the end of this paper.

The contrast should be obvious, i.e., a minimum increase of 100% in mason output. Considering the high labor to material ratio of 3 to 1 as pointed out earlier, this significant reduction of labor costs makes a strong impact on the overall finished wall cost.

3. Conclusions

The data presented here has shown that a new concept in construction will be accepted by a tradition-bound industry if the concept is sound and the data to support that concept are available. By establishing criteria on a performance basis, and generating the necessary data to meet that criteria, a seemingly radical departure from conventional methods becomes an accepted and sought-after technique.

4. References

[1] National Concrete Masonry Association, "Specification for the Design and Construction of Load-Bearing Concrete Masonry," 1971.

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[10] Yokel, Felix Y., Mathey, Robert G., and Dikkens, Robert D., "Compressive Strength of Slender Concrete Masonry Walls," Building Science Series 33, National Bureau of Standards, 1970.

[11] Structural Reports by Schupack and Association, July 16, 1965.

[12] Letter Report on Compressive Prisms, National Concrete Masonry Association, May 18, 1971.

[13] Prism Tests by Bonded Testing Company, Honolulu, Hawaii, August, 1969.

[14] Unpublished Structural Test Data on Concrete Block and THREADLINE Brand Mortar, National Bureau of Standards, May 22, 1970.

Table 1

Wall Tests with Conventional Mortar

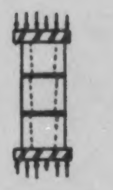
ASTM E 72

					Test Results from Wall Samples								
					Compression			Uniform Transverse Bending			Racking		
		Characteristics of the Block											
Data Source	Mortar Type**	Thickness in.	Aggregate	Compressive Strength psi	No. of Samples	Wall Strength psi	% Block Strength	No. of Samples	Transverse Load psf	Modulus of Rupture psi	No. of Samples	Load/ Length $\mathrm{Lb\ ft^{-1}}$	Shear Stress* psi
(3)	M	8	Expanded shale	1400	1	638	46	1	60	44	-	-	-
(3)	S	8	Expanded shale	1450	1	549	38	1	35	25	-	-	-
(3)	S	8	Expanded shale	1165	1	480	41	1	32	23	-	-	-
(4)	M	8	Sand-gravel	1210	-	-	-	3	89	65	-	-	-
(4)	S	8	Sand-gravel	1210	-	-	-	3	65	47	-	-	-
(4)	O	8	Sand-gravel	1210	-	-	-	2	39	28	-	-	-
(5)	N	8	Sand-gravel	2160	-	-	-	1	42	30	-	-	-
(6)	N	6	Expanded slag	1020	1	370	31	1	11	15	1	1810	27
(7)	M	8	Unreported	1190	-	-	-	-	-	-	1	3180	35
(5)	N	8	Sand-gravel	2900	-	--	-	-	-	-	1	2690	30
(8)	N	8	Gravel	1230	1	695	57	-	-	-	-	-	-
(3)	N	8	Slag	1290	1	540	42	-	-	-	-	-	-
(8)	N	8	Haydite	1280	1	440	34	-	-	-	-	-	-
(8)	"C"	8	Cinder	1150	1	610	53	-	-	-	-	-	-
(8)	C	8	Gravel	1570	1	780	50	-	-	-	-	-	-

*Based on gross area.

** ASTM C 270

Table 2. Compressive Prism Tests



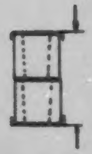
		Characteristics of the Block			Test Results of Prisms				
Data Source	Mortar** Type	Thickness	Aggregate	Compressive Strength*	No. of Samples	End Conditions	Height	Compressive Strength*	% of Block Strength
[9]	S	8"	Expanded shale	1440 psi	5	Fixed	2 block	1135 psi	79%
[9]	S	8"	Expanded shale	1440	5	Fixed	3 block	1020	71
[9]	S	8"	Expanded shale	1440	5	Fixed	5 Block	1040	72
[9]	N	8"	Expanded shale	1440	5	Fixed	2 block	1110	77
[9]	N	8"	Expanded shale	1440	5	Fixed	3 block	925	64
[9]	N	8"	Expanded shale	1440	5	Fixed	5 block	770	53
[9]	S	8"	Expanded shale sand	2090	5	Fixed	2 block	1650	79
[9]	C	8"	Expanded shale	2090	5	Fixed	2 block	1412	68

*Based on gross area.
** ASTM C 270

Table 3. Bond Tests

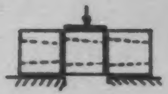
Tensile Bond Test

ASTM E-149



		Characteristics of the Block				
Data Source	Mortar*** Type	Thickness	Aggregate	Compressive Strength*	No. of Samples	Tensile Bond**
[4]	N	8"	Sand-gravel	1010-2160 psi	16	37 psi
[4]	N	8"	Expanded shale	1270	8	45
[4]	M	8"	Sand-gravel	1010-2160	10	69
[4]	M	8"	Expanded shale	1270	6	87
[4]	S	8"	Sand-gravel	1010-2160	3	116
[4]	C	8"	Sand-gravel	1010-2160	7	5

Shear Bond Test



		Characteristics of the Block				
Data Source	Mortar Type	Thickness	Aggregate	Compressive Strength*	No. of Samples	Shear Stress**
[4]	M	8"	Sand-gravel	2060 psi	5	69 psi
[4]	N	8"	Sand-gravel	2060	5	34
[4]	S	8"	Sand-gravel	2060	5	24

* Based on gross area.

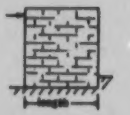
**Net bedded area of face shells.

*** ASTM C 270

Table 4

Wall Tests with Adhesive Type Mortar

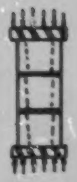
ASTM E-72

					Test Results from Wall Samples								
		Characteristics of the Block			Compression			Uniform Transverse Bending			Racking		
													
Data* Source	Mortar Type	Thickness in.	Aggregate	Compressive Strength** psi	No. of Samples	Wall Strength** psi	% Block Strength	No. of Samples	Load psf	Modulus of Rupture psi	No. of Samples	Load/ Length Lb ft^{-1}	Shear Stress** psi
(14)	Adhesive	6	Expanded shale-sand	1476	2	770	52	2	130	175	-	-	-
(5)	Adhesive	8	Expanded slag	1190	-	-	-	1	208	138	-	-	-
(5)	Adhesive	8	Expanded slag	1190	-	-	-	1	224	148	-	-	-
(11)	Adhesive	8	Expanded slag	1190	-	-	-	-	-	-	1	5100	56
(5)	Adhesive	8	Sand-gravel	2160	-	-	-	1	270	190	-	-	-
(5)	Adhesive	8	Sand-gravel	2700	-	-	-	1	364	260	-	-	-
(5)	Adhesive	8	Expanded shale	1305	-	-	-	3	166	110	-	-	-
(5)	Adhesive	6	Expanded shale	1400	-	-	-	1	144	194	-	-	-

*Data sources are literature references at the end of this paper.

**Based on gross area.

Table 5. Compressive Prism Tests



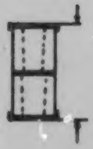
Data Source	Mortar Type	Characteristics of the Block			Test Results of the Prisms				
		Thickness	Aggregate	Compressive Strength*	No. of Samples	End Conditions	Height	Compressive Strength*	% of Block Strength
[14]	Adhesive	6"	Expanded shale-sand	1476 psi	3	Fixed	2 block	1260 psi	85
[14]	Adhesive	6	Expanded shale sand	1476	3	Fixed	3 block	1100	75
[12]	Adhesive	8	Expanded shale	1490	5	Fixed	2 block	1000	67
[12]	Adhesive	8	Expanded shale	1490	3	Fixed	5 block	1060	71
[12]	Adhesive	8	Expanded shale-sand	2090	5	Fixed	2 block	1436	69
[13]	Adhesive	8	Limestone	1062	30	Fixed	2 block	938	87

*Based on gross area.

Table 6. Bond Tests

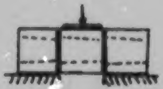
Tensile Bond

ASTM E-149



Data Source	Mortar Type	Characteristics of the Block Thickness	 Aggregate	 Compressive Strength*	No. of Samples	Bond**
[14]	Adhesive	6"	Expanded shale	1476 psi	5	202 psi

Shear Bond Test

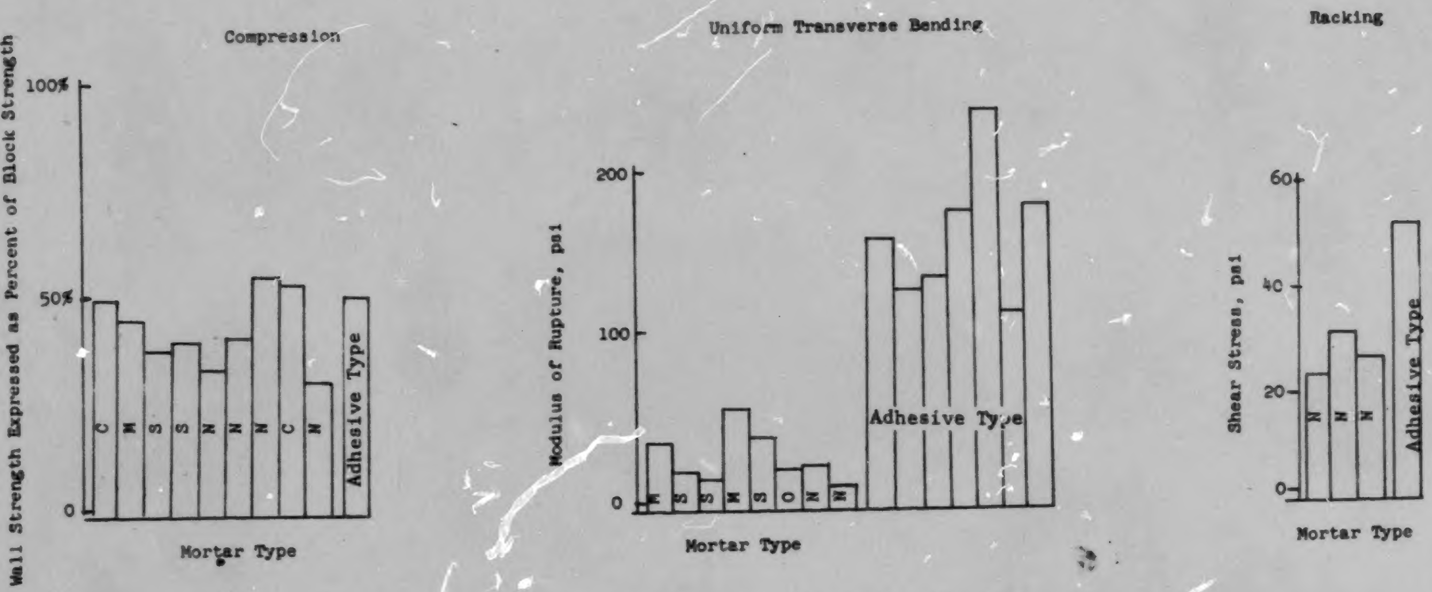


Data Source	Mortar Type	Characteristics of the Block Thickness	 Aggregate	 Compressive Strength*	No. of Samples	Shear Stress**
[9]	Adhesive	8"	Sand-gravel	2700 psi	5	825 psi
[10]	Adhesive	8"	Expanded shale-pumice	1610	1	360
[10]	Adhesive	6"	Sand	1180	1	550

*Gross area.

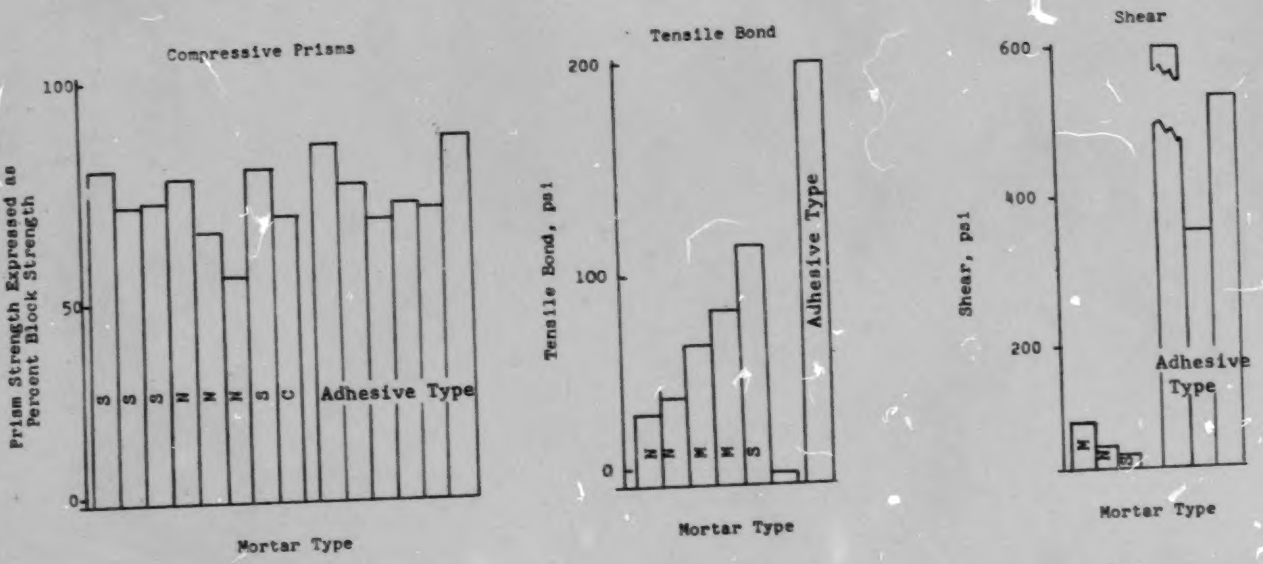
**Net bedded area.

Table 7. Summary and Comparison of Wall Test Data



Data from tables 1 and 4 identified respectively by mortar type.

Table 8. Summary of Comparison of Small Scale Tests



Data from tables 2,3,5,6 identified respectively by mortar type

Table 9.

CASE HISTORY - 65-3

JOB - Ortense Lumber
Wallingford, Connecticut

GENERAL CONTRACTOR - Ortense Inc.
Wallingford, Connecticut

MASON CONTRACTOR - G. Verni & Sons
Ansonia, Connecticut

ARCHITECT - Customer's Own Design Engineers

TYPE CONSTRUCTION - Ground cinder block and
Adhesive mortar

CONSTRUCTION DATE - December 10, 1965

TYPE JOB

Machine shop and Warehouse.

BUILDING SIZE

128' Long x 60' Wide x 14' High

LABOR AND MATERIAL COSTS* (estimated vs. actual)

1. Conventional mortar estimate, by Ortense Inc., for 12 x 8 x 16 cinder block with portland cement-sand mortar.

A. Materials

5360 block	@ $.36	$1929.60	
Mortar	@ .05	268.00	
Joint reinforcing	@ .03 =	160.00	
Total Material Cost			$2,357.40

B. Labor

3 masons @ $4.85 per hour for 12 days	$1500.00	
3 laborers @ $3.75 per hour for 12 days	1080.00	
Total Labor Cost		$2,580.00
Total estimated cost		$4,937.40

Cost per square foot of wall $\frac{\$4937.40}{4764 \text{ ft}^2}$ = $1.04 ft^2

2. Actual cost, with ground cinder block and Adhesive mortar.

A. Materials

5360 block	@ $0.42 =	$2251.20	
Mortar	@ .08	428.80	
Total Material Cost			$2,680.00

Table 9 continued

B. Labor

3 masons @ $4.85 per hour for 6.5 days	$ 814.00	
3 laborers @ $3.75 per hour for 6.5 days	585.00	
Total Labor Cost		$1,399.00
Total Material and Labor Costs		$4,079.00
Cost per square foot of wall		
*USA Dollars	$\frac{\$4079.00}{4764 \text{ ft}^2}$	$0.86 ft^2

SUMMARY:

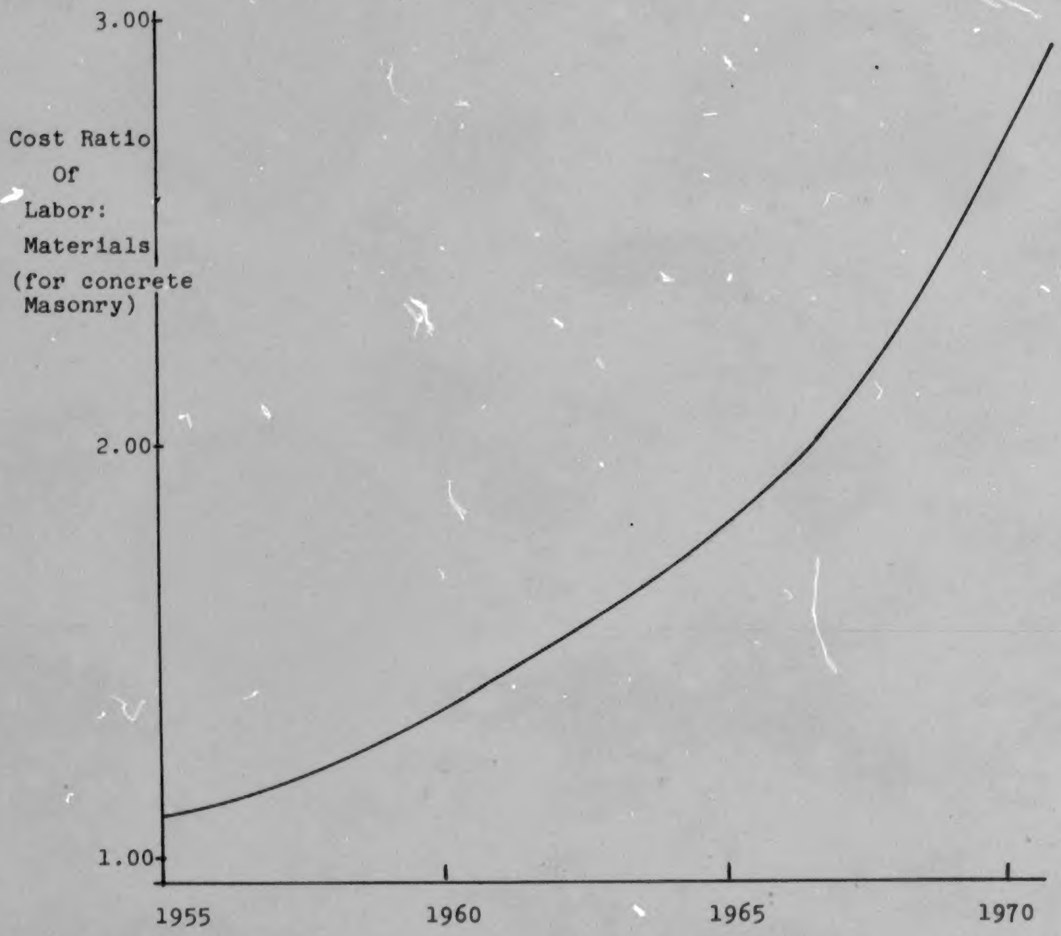
	Total Materials & Labor	per square foot of wall
Conventional mortar estimate	$4,937.40	$1.04
Adhesive mortar & ground block	4,079.00	.86
Savings	$ 858.40	$ .18

Table 10. Mason Productivity On Representative Projects

Project	Date Constructed	Type of Wall	Mason Productivity Block per man per day	
			Sand-Cement*	Adhesive Mortar
Alexander Arms Honolulu, Hawaii 14 story apartments	1970	high-rise load-bearing, reinforced for seismic requirements	175	300-350
Village West Louisville, Kentucky Garden apartments	1969-1970	2 and 3 story loed-bearing, partially prefabricated	300	700
Lattie Building New Orleans, La. 10 story office	1970	Curtain Wall	150	300
Heather Ridge Denver, Colorado Garden apartments	1971 (under construction)	4 story load-bearing prefabricated	300	600
Travel Lodge Orlando, Florida 18 story hotel	1971 (under construction)	high-rise load-bearing, reinforced	200	350
Prospect Towers Apartments Waterbury, Conn. 11 story housing for the elderly	1970	high-rise load-bearing	300	550

*Estimated by local representatives

Figure 1. Ratio Of Labor To Materials Costs
For [2]
8 Inch Concrete Block Wall Construction



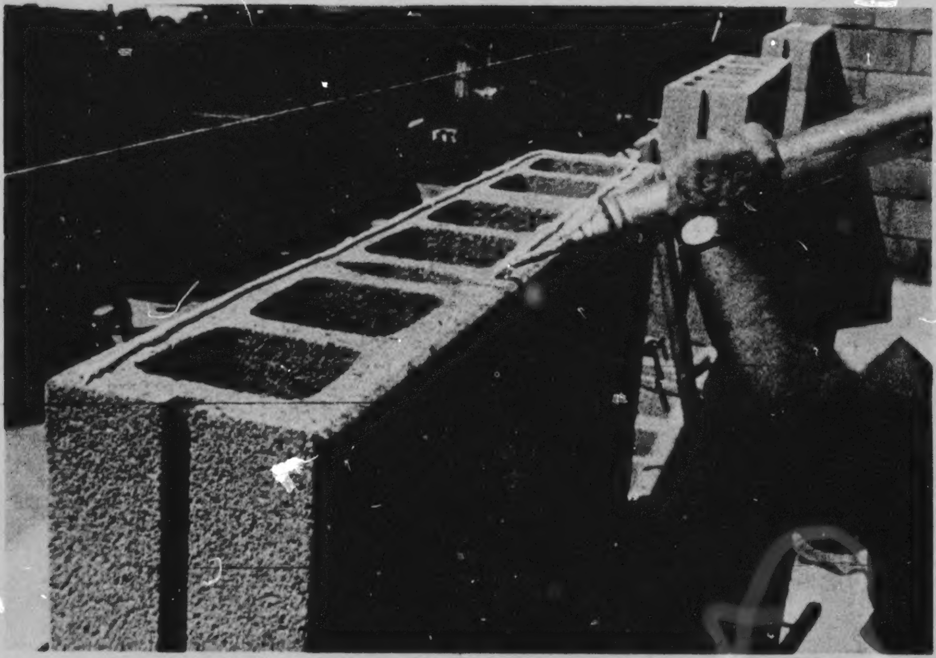
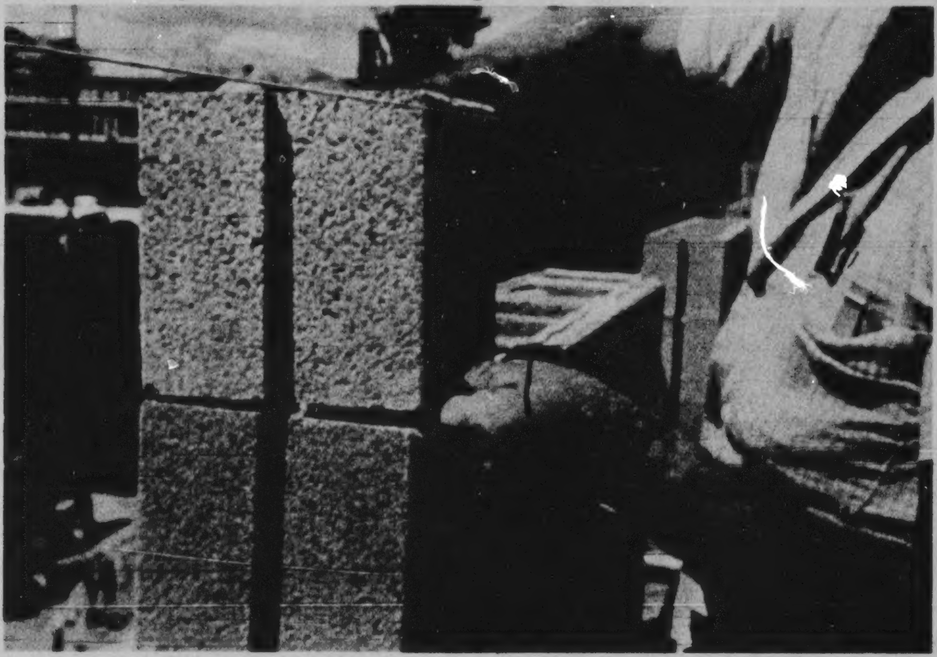


Fig. 2 Adhesive Mortar being applied to the bedjoint surface of ground block (blocks have a bevel at the edge of the bedjoint surface to simulate a conventional mortar joint).

Fig. 3 A ground block being laid in the adhesive mortar



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Performance Requisites For Concrete Building Components And Their Achievement With Gap-Graded Concrete

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Performance requirements for all reinforced and prestressed concrete building components are established and criteria for evaluating such performance requirements are given. Their achievement with gap-graded concrete is substantiated with experimental results and field observations.

Les exigences de performance pour tous les composants de construction en béton armé et précontraint sont établies spécifiquement pour piles, chapiteaux, murs de soutènement, colonnes, poutres murs non revêtus et panneaux à agrégats apparents, planchers et toits. Critères et techniques sont donnés pour l'évaluation et la prévision de telles exigences de performance. Leur réalisation avec un béton à granulométric discontinue est établie à tous égards.

Key words: Aggregate grading; cement content; concrete construction; creep; durability; economy; gap-grading; shrinkage; strength; structural concrete.

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1. Introduction

Concrete is now being used in greater quantities in medium-rise and moderately high-rise buildings than any other man-made building material. It has become indispensable in practically all types of buildings and many of their supporting components. The demands for housing and other building programs will continue to increase. It is estimated, for example, that even if the population increases only 50 percent in the United States of America in the next 30 years, a new living unit will be needed every 20 seconds, requiring very large quantities of concrete.

Additionally, concrete has the unique advantage that the engineer can formulate the mixture within limits, to meet specific requirements for durability, strength, finishability, etc. Important as are the merits of conventional continuously-graded concrete used hitherto, a number of performance improvements and the behavioral efficiency of building components could be much enhanced by using concrete which is gap-graded.

For more than two decades, there has been a growing appreciation, in Europe and elsewhere, of a mathematical approach to mix design known as gap-grading(1-7)[4]. In principle, the aggregates are considered in two parts, (1) the main body, which constitutes 65 to 75% of the combined aggregates and is composed of single-sized 1 1/2", 3/4" or 1/2" material, and (2) a fine aggregate or filler representing 35 to 25% of the combined aggregates. The sizes of the coarse and fine aggregates are so related as to allow the whole of the filler to pass freely into and through all the voids in the compacted coarse aggregate. Thus, one cubic yard of coarse aggregate will produce approximately one cubic yard of concrete, the filler (sand), cement and water filling the interstices of the particles of coarse material. From this it is clear that to design a gap-graded concrete the bulk density of the coarse aggregate must be determined in relation to the general placing conditions. From this data and the relevant specific gravity, the percentage voids can be calculated and hence the volumes or weights of filler, cement, and water can be found to meet the requirements of strength and workability specified.

The extensive research results (9-20) and field observations made by the authors in the U.K. and U.S.A. have proved that gap-graded concrete, even though with a relatively stiffer and drier mix, could be placed and finished without undue effort for all constructions wherein continuously-graded concrete has been used heretofore.

A considerable saving in cement requirement and significant improvements in physical and mechanical properties are the realistic advantages achievable through the use of gap-graded concrete for whatever purpose conventional concrete is called for.

This paper discusses the performance requirements for all reinforced and prestressed concrete building components. Their achievement with gap-graded concrete has been substantiated by experimental results and field observations.

2. Performance Requisites for Reinforced Concrete Building Components

The major performance requisites for reinforced concrete building components are listed in Table 1.

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[4] Figures in brackets indicate the literature references at the end of this paper.

3. Performance Requisites for Prestressed Concrete Building Components

All the performance requisites for reinforced concrete building components apply to the equivalent prestressed concrete building components.

However, there are four most significant performance requisites for prestressed concrete as compared to reinforced concrete that must be recognized. These are (1) higher strength, (2) higher moduli of elasticity and rigidity, (3) lower shrinkage, and (4) lower creep, which are always more easily and reliably attained with gap-graded as compared with continuously-graded concrete. The latter three help reduce prestress losses to a minimum. These superior physical and mechanical properties of gap-graded concrete make it the ideal material for prestressing.

Additionally, in all precast prestressed elements, the much lower form pressure and much earlier form stripping that are possible with gap-graded concrete, permit it to be cast with less form expense, more strict tolerance, and higher turnover for form reuse.

4. Criteria for Evaluating Performance Requisites

The criteria for evaluating performance requisites are the workability and finishability tests for the fresh concrete, and the various standard tests for determining the physical and mechanical properties of hardened concrete, such as compressive strength, tensile strength, elastic modulus, creep, shrinkage, permeability, unit weight, wear- and skid-resistance, etc. Among these, workability and compressive strength are the most important. This is because other attributes of concrete such as durability, permeability, wear resistance, and tensile strength are all more or less related to compressive strength. For rapid assessment, the 7-day or even one-day compressive strength can be correlated with the 28-day compressive strength for concrete made with the same materials.

Recent advances and developments in nondestructive testing and evaluation have evolved various methods and techniques for determining performance characteristics not only in test specimens but also in prototype structures in service.

5. Achievement of Performance Requisites with Gap-Graded Concrete

5.1 Experimental Results

In order to ascertain the performance characteristics of gap-graded concrete in comparison with the conventionally used continuously-graded concrete, an extensive investigation was carried out by two of the authors (Li and Ramakrishnan) (9-18,20). In this investigation, 375 mixtures of gap-graded and continuously-graded concretes, in the strength range of 3000 psi to 7500 psi were used. There were four different maximum sizes of coarse aggregates (1 1/2", 1", 3/4", and 1/2"), water-cement ratios varying from 0.35 to 0.65, and aggregate-cement ratios varying from 2 to 10. The tests were conducted, whenever applicable, according to ASTM Standard Methods.

A comparison of the results for gap-graded versus continuously-graded concretes on the basis of equal maximum size of coarse aggregate, water-cement ratio, and aggregate-cement ratio has shown the relative ease of placing gap-graded concrete to attain uniform compaction. A study of the efficiency of slump test versus Vebe time as a measure of workability has revealed that Vebe time should be used for evaluating the workability of gap-graded concrete.

For equal compressive strength, maximum size of coarse aggregate, and approximately equal workability, gap-graded concrete has higher unit weight, higher modulus of elasticity, less shrinkage, less creep, and less permeability than continuously-graded concrete. The study has also shown that for equal maximum size of coarse aggregate, gap-graded concrete can be produced with at least 20 to 30 percent less cement than continuously-graded concrete to give the same compressive strength.

The comparison of expansion-shrinkage characteristics of gap-graded and continuously-graded concretes made with type-k shrinkage-compensating cement, has shown that continuously-graded, shrinkage-compensating concrete, whether unrestrained or with lateral reinforcement (1.16 percent steel), requires about 40 percent more type-k cement than the equivalent gap-graded shrinkage-compensating concrete having the same compressive strength and workability.

5.2. Field Observations

To the practical engineer in the structural and construction fields, it must be evident that concrete cannot be thought of in isolation from the formwork in which it is to be placed or the steel with which it shares the induced stresses. It is also true that it is unwise to consider concrete mix design on the basis of merely compressive strength alone because, with a high performance cement, the water-cement ratio at which the required strength can be attained is unnecessarily high and hence a potential for excessive shrinkage, creep, or both, exists. In spite of this the majority of concrete specifications are determined on the compressive strength after a particular lapse of time, together with some reference to workability, and such physical properties of the combined materials as shrinkage and creep are seldom, if ever, mentioned.

It is not that these phenomena are not recognized or understood, for research has established that they are intimately associated with the proportioning of the constituent materials of the concrete, but that the usual basis of mix design is empirical and hence is divorced from the science of this subject. It is also associated, one fears, with a lack of site experience in placing and compacting concrete by the bulk of designers and detailers of reinforced concrete structures, and aggravated by a lack of training of the labor force actually manipulating the concrete.

Vibration is now virtually universally applied in placing concrete whether in the field or in the precast factory. Where internal vibrators are employed, consideration must be given to the distribution of the steel in the various members to be formed so that not only the concrete but also the vibrators can be easily introduced into the forms. There is also an association between the diameter of the internal vibrator and the volume of concrete to be dealt with per insertion as well as the relationship of the maximum aggregate size to this diameter. For example, no one would really consider using a 1 1/2" vibrator in dam construction where the concrete contained 6" aggregate.

In reinforced concrete structures with heavy reinforcement, it should be remembered that the steel itself absorbs energy from the vibrator by virtue of transmission through the concrete. Consequently, as the effectiveness of a poker is proportional to the square of its diameter (centrifugal force times surface area), a poker of less than 2 1/2" may prove rather inefficient in terms of the ultimate quality of the concrete. This is particularly true of continuously-graded concretes where the use of high mortar contents are common. Because we live in an age of rapidly advancing technology, it has been considered desirable to comment on the somewhat haphazard approach of the construction industry to the actual production of reinforced concrete building components.

As to the advantages gap-grading has given over continuous-grading, the two following examples point very clearly:

The production of road pavements in India, in many areas, was becoming frighteningly expensive because the Authority insisted on the use of sand conforming to a British Standard specification. This meant that frequently the local fine sand was not acceptable and hauls of up to 200 miles were necessary to bring in sand of an acceptable grading. The Indian Road Research Laboratory, after studying Stewart's work (1-3) on gap-grading, decided to make their own tests. These showed such promise that in a short time standard gradings were discarded and local sands were brought into use producing completely acceptable concrete to which could be credited the reduced haulage and cement costs.

Apart from demonstrating that a logical approach to the formulation of concrete grading reduced cost and even improved quality, it shows the danger of either a Central or Local Authority introducing Codes of Practice which specify in detail rather than in principle and thereby preventing the engineer from pursuing his profession, to the full, the economic use of natural resources.

The second example involves the resistance of gap-graded concrete to plastic deformation after it has been fully compacted. A wind tunnel was to be constructed of reinforced concrete. The air circuit was over 400 yards and the test section had a cross sectional area of 13' x 9', the main tunnel being octagonal in form. The specification required that the internal surface be smooth and free of all pits which could cause local turbulence. No patching or repair of the hardened concrete was permitted. Such a finish could not be achieved on the lower sloping planes or the vertical panels immediately above them.

It was decided to carry out the construction with gap-graded concrete and to strip the inner forms, each 20' x 14' deep and 6" thick, immediately after placing and compacting the concrete. This was done and the green concrete tunnel surface was trowelled to a smooth grano-like finish which was cured as soon as sufficiently hard.

The concrete used in this project was 1 1/2" single-sized aggregate and a local sand all passing No. 4 sieve U.S. range. The A/C ratio was 8:1 and the W/C ratio 0.56, giving an average cube strength of 5800 psi at 28 days. There was also a saving of over 100 lb of cement per cubic yard.

We know from experience in the U.K. that gap-graded concrete used in sea defences has a much higher resistance to deterioration and erosion than much more costly conventional concrete.

Unfortunately, it is not always easy to get the professions to accept what appears to be new ideas. In fact, one of the hardest tasks that an engineer can undertake is to transfer a technique from the laboratory to the field where an established procedure is in general use. It does not matter that the new approach can effect appreciable savings; the fact that it is new will make it be viewed with suspicion by many and hence man will be denied a better and less expensive product.

6. Advantages of Gap-Graded Concrete

The inherent advantages of gap grading and gap-graded concrete are as follows:

1. Any sound coarse and fine aggregates will make good gap-grading provided that the size ratio of the coarse aggregate to the fine

is such that the latter can be admitted to the side interstices of the former during compaction.

2. Gap-grading can best use all available sizes. For example, in a building project, the largest sizes of gravel or crushed stone can be used in footings and retaining walls, the medium sizes in heavy girders and columns, and the smaller sizes in beams and slabs.

3. Gap-grading provides a unique solution to the depletion of naturally occurring continuously-graded aggregates.

4. Gap-grading reduces segregation to a minimum and provides greater uniformity of quality. Hence, quality control of the concrete is much easier and better for a given control effort. A smaller value of standard deviation may thus be used for a required probability of failure.

5. Once compacted the concrete has a higher resistance to deformation in the fresh state as compared with traditional concrete. This allows appreciably lower pressures to be used in the design of formwork, the value being about 600 lb/ft^2 for continuous pouring up to 30' at a rate of 10 to 15 yds^3/hr.

6. Because of 5. above, vertical forms can be stripped within two hours or less of completion of the pour. This allows exposed aggregate finishes to be produced in situ and avoids the concrete at stop-ends having to be hacked. No retarders or accelerators are necessary.

7. Any structural floor slab can be walked on immediately after placing without the surface being deformed. Hence, any type of finish, such as grano, can be placed and trowelled off immediately after the section has been placed and compacted.

8. Because both shrinkage and creep are less in gap-graded concrete, larger areas of floor slab or pavement can be laid at one time, making crack control cheaper.

9. The advantages to be gained in pre- and post-stressed units due to reduced shrinkage and creep are obvious.

10. Gap-grading can improve concrete blocks by virtue of less shrinkage and reduce their cost as a result of lower cement requirement.

11. Gap-grading is imperative for precasting exposed aggregate wall panels, as has been done for more than three decades, to show the exposed aggregate more uniformly and more prominently.

12. Gap-grading is the only logical grading for manufactured lightweight aggregate which can be most expediently produced in equal size. Uniform size of coarse aggregate is the mathematically ideal size for gap grading to save the maximum amount of cement.

13. Gap-grading can reduce the cost of shrinkage-compensating concrete.

14. Gap-grading can considerably improve the physical and mechanical performances of building components by virtue of lower shrinkage, lower creep, higher compressive strength, and higher moduli of elasticity and rigidity for the same cement content and the same maximum size of coarse aggregate.

Table 1. Major performance requisites for reinforced concrete building components

Building Components	Specific Performance Requirements	Performance Requirements Common to All Components
Piles	High modulus of elasticity, low creep, impermeability	Adaptability to any sound aggregates High Strength Low Cement Requirement
Pile Caps	Same as above	
Footings	Same as above	
Retaining Walls	Same as above	
Columns	High modulus of elasticity, low creep, low shrinkage, durability, earlier form stripping, finishability	
Girders and Beams	High modulus of elasticity, high modulus of rupture, low creep	
Shear Walls	High modulus of rigidity, low creep, durability, earlier form stripping	
Floors and Roofs	Same as above plus low shrinkage, finishability	
Architectural Panels	Uniform exposure of coarse aggregate, durability	
Side Walks and Pavements	Durability, finishability, low shrinkage, high wear resistance, high skid resistance (associated with shape, hardness and crystalline structure of coarse aggregate)	

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Relating Materials Quality to Materials Performance to Structural Performance of Concrete

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Portland cement, aggregates for portland-cement concrete, admixtures for concrete, and curing materials for concrete are usually procured for use in construction under specifications that stipulate levels of quality as indicated by the results of standardised tests of samples. The information obtained from these tests is believed to be related directly or indirectly to levels of performance of the material itself, the composite of which it is a constituent, the structural element of which it is a component, and the structural system of which it is an element. The testing is limited to determinations that can be completed in the time available for testing and at an appropriate cost. The levels of quality are selected to be few for simplicity and are frequently higher than needed to insure adequacy of performance in the specific situation; rarely lower. Attention has primarily been directed to those few cases where less than adequate performance has resulted. Greater economies and more prudent utilisation of natural resources will result if attention were directed to those much more numerous cases where stipulated levels of quality are higher than needed.

Le ciment de Portland, les agrégats pour le béton de ciment de Portland, les adjuvants et les agents de traitement du béton sont généralement produits pour une utilisation dans la construction selon des spécifications qui stipulent des degrés de qualité établis suivant les résultats d'essais normalisés sur des échantillons. L'information fournie par ces essais est supposée être en relation directe ou indirecte avec les niveaux de performance du matériau lui-même, du composé dont il est l'un des constituants, de l'élément de structure dont il est un composant et du système structural dont il est un élément. Les essais se limitent à des déterminations qui peuvent être effectuées dans le temps disponible et à un coût approprié. Pour simplifier, on définit un petit nombre de degrés de qualité, qui sont souvent plus élevés qu'il ne serait nécessaire pour assurer une performance adéquate dans une situation donnée: rarement sont-ils plus bas que nécessaire. L'attention s'est surtout portée vers les rares cas où une performance insuffisante a été obtenue. De plus fortes économies et une plus prudente utilisation des ressources naturelles résulteraient si l'attention était dirigée vers ces cas beaucoup plus nombreux où les degrés de qualité stipulés sont plus élevés que nécessaire.

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Key words: Aggregates; cement; concrete; concrete quality; materials; performance; portland cement; structural performance.

1. Introduction

This symposium on "The Performance Concept in Buildings" provides a most appropriate forum in which to re-examine the validity of the implicit assumption that the levels of quality of materials required by purchase specifications do insure the appropriate levels of performance of these materials in the composite of which they form a part, of that composite in the structural element of which it is a component, and of that element in the structural system or building of which it is an element. Other contributors to this symposium will review the criteria upon which structural systems or buildings are planned, designed, and specified to have the selected dimensions, location, orientation, and other features generally related to user needs. This paper addresses the criteria upon which the concrete that will be used in a structural system or building is selected and specified.

2. Aggregates for Concrete

Typically, as indicated for example by Section 403 of the 1963 ACI Building Code (1)[2], aggregates for concrete for reinforced concrete buildings are required to conform to a general specification, in the example ASTM C 33, Specifications for Concrete Aggregates (2). However, Section 403 provides an escape clause reading "except that aggregates failing to meet these specifications but which have been shown by special test or actual service to produce concrete of adequate strength and durability may be used...where authorized by the Building Official." These statements are not changed in the 1971 Code (3).

ASTM C 33 includes a note to its scope, which note reads "This specification is regarded as adequate to ensure satisfactory materials for most concrete. It is recognized that, for certain work or in certain regions, they may be either more or less restrictive than needed." Much of the concrete in buildings does not need to resist the action of freezing and thawing when in a wet condition; in fact, relatively very little concrete in buildings must be able to resist such an exposure in order to provide satisfactory performance. Nevertheless, ASTM C 33-71 requires (Section 5) that fine aggregate must be tested by the sulfate soundness procedure and not exhibit more than a stipulated amount of degradation—or have a satisfactory service record—or perform satisfactorily in a freezing and thawing test. No option is given, other than through the general note to the scope, for waiving the soundness provisions when they are inapplicable.

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[2] Figures in parentheses indicate the literature references at the end of this paper.

The criteria for selection of aggregates for concrete need to be revised so that the levels of "quality" as measured by standard tests and the tests selected for such measurement are varied to relate to the performance required of the concrete in the service environment of the building in which the concrete is used. This concept was stated by ACI Committee 621 in 1961 (4) in these words: "In selecting an aggregate it is economical to require only those properties pertinent to its use in a particular project." This is not the practice today.

3. Cement

The purchase specifications for portland cement were referred to by P. H. Bates in 1940 as being "as good as an outline of research, through their inadequacies, as they are good purchase specifications" (4). Mr. Bates spoke of the activities of the user of cement in these terms: "He must determine which type (of cement) he should use in any case by studying the conditions under which he will use the cement, the conditions during its later life, and the requirements in the standard wherein the nature of the several types is given. In many cases the choice is simple and can be quickly made. A high-early-strength cement would hardly be selected if there is no need for haste in construction or in placing the finished structure in use. A low-heat or sulfate resisting cement would hardly be selected for a reinforced concrete frame building to be covered with brick or stone" (4). This, I suggest, is the performance concept in building--related, more than 30 years ago, to the purchase specifications for cement. Yet, today the degree to which we are able to employ this concept efficiently is not very great. In 1970, I wrote the following: (5)

"Cement and concrete obtained by the intelligent use of current standards will yield, together with competent structural design and construction practice, structures that will in nearly all cases serve well their intended purposes. However, current specifications for portland cement of any given type allow products of an amazingly wide variation in levels of relevant properties to be offered in terms that could lead to substantial difficulties if they were substituted one for another as is sometimes attempted.

"In a letter received this spring from a distinguished engineer and past president of the American Concrete Institute, I found these comments.

> I have observed considerable variation in the quality of concrete produced by various brands of cement....The cement industry is suffering serious economic problems throughout the country....The depressed condition of the cement industry, in my opinion, can be attributed to the attitude of the consumers of cement, and this sad state of affairs will continue as long as low quality standards prevail, with the price per barrel as the yardstick for marketing.... We have measured the quality of the cements by their performance in producing high-quality concrete for us. Naturally, if Brand X can achieve our objectives with 25 lb less per cubic yard than Brands Y or Z, we buy Brand X. If the choice of brand is left to the contractor, he will buy the cheapest, which encourages low cost rather than high quality. I am not sure that the present ASTM tests are the best way to measure quality. In our experience, the most successful measure is the quality of the concrete, as made with our aggregates. The cement industry needs incentives for innovation and technological breakthroughs. It must shift its emphasis from price to technical excellence. To do this the customer should provide the rewards.

"Edward Cohen, vice-president of the American Concrete Institute and chairman of its Building Code Committee, writing in the February 1970 issue of Materials Research and Standards as a designer of concrete structures, said, 'More research is needed to incorporate the variety of cement properties into the art of cement production. It is common knowledge that cements coming from certain areas of the country are preferable to others--- The designer should be given the opportunity to specify that type of cement which best meets his structural and economical requirements.'

"The project manager for the contractor on the largest Corps of Engineers construction project now going on, speaking in March 1970 at the Engineering Foundation Conference on Rapid Construction of Concrete Dams, noted as the first item in a list of 'most promising areas' for cost reduction in construction of dams 'better control and raising of strength requirements of cement--and optimization of SO_3 content or any other component to ensure maximum response to admixtures to aid in better utilization of strength properties of portland cement concrete.'"

4. Concrete

If the environment of service imposes tensile stresses on the concrete that exceed its tensile strength, one or more cracks will form. If a given crack is one that interferes with the rendering of satisfactory service by the concrete, it is desirable that there be an investigation to establish whether the error that was made that allowed the conditions to develop that required the crack to form was in (a) estimating the stresses that would be imposed, (b) estimating the strength that would be required, (c) selecting concrete materials and proportions to give the strength estimated to be required, or (d) producing concrete having the strength estimated to be required. Note that there are four stages where error can occur; stated more generally these are:

1. Evaluating the environmental severity.

2. Selecting the quality level of relevant properties appropriate to the environmental severity.

3. Selecting materials and proportions to yield concrete of the appropriate quality level of relevant properties.

4. Getting concrete of the desired quality.

Stated bluntly, when concrete fails to behave properly, the questions are: (a) Did you order what you should have ordered? (b) Did you get what you ordered? i.e., should you properly blame yourself or the contractor for the trouble you are in?

Figure 1 was prepared to show the relationship between concrete properties and concrete behavior. It assumes that concrete, a material, is an element of a system such as a building. It further assumes that the concrete is desired to behave in a given manner if the performance of the system of which it is a part will be satisfactory. Thus starting in the center of the bottom of the diagram with "performance of the system," we assume that from the criteria applicable thereto one can establish what performance is desired of the concrete. Knowing the desired level of performance, we should be able to establish the desired--and needed--level of relevant properties, provided we also know the level of the environmental influences that will act upon it. When the desired levels of relevant properties are established, the specification requirements for materials properties, materials proportions, and construction practices may be set. Once these requirements have been stipulated, and enforced, the result will be the production of concrete having such levels of appropriate properties that, as the concrete interacts with the environment, its behavior in service will be such that its achieved performance will equal the desired performance and the performance of the system of which it is a portion will be satisfactory.

In the present state-of-the-art of concrete making, it is not possible to state, without reservation, that a particular concrete mixture is uniquely the most economical that could be specified and produced at a given time in a given place, to be placed at a given location in a particular structure. The techniques for evaluating the environment conditions to which that concrete will be subjected during its service life do not permit precise calculations. We can estimate dead loads rather accurately; live loads somewhat less accurately. Earthquake forces are becoming better understood. Foundation interactions are often quite poorly predictable. Chemical attack and weather severity are evaluated generally only in qualitative terms. Since we cannot evaluate environmental conditions with precision, we could not select appropriate levels of quality to match environmental severity even if we had a perfectly precise basis for relating concrete quality levels to degrees of combined and classified environmental severity. We are in better shape when it comes to selecting materials and their proportions to yield predictable quality levels of concrete properties, but in some areas even here we can only deal in qualitative terms. Finally, there is quality control and inspection; the point at which we try to have assurance that we are getting within proper limits, what we ordered and are paying for. A great deal of progress has been made in this area rather recently (6).

Milo Ketchum commented on the relation of concrete strength and building performance in part as follows (7):

"High strength, alone, has very little advantage for ordinary reinforced concrete buildings. If proper production control could be maintained, a nominal cylinder strength of 2500 psi (at 28 days) should be satisfactory for most concrete structures, and this can be achieved with a minimum cement content. High strength, however, is a symbol for other desirable properties and a pledge that the concrete will have enough cement. Ultimate strength design for sections of concrete members has demonstrated to the design profession that concrete seldom fails in compression. We specify the higher strength because of the non-uniformity of test results and because it is insurance against concrete that would have to be removed from the structure. Considering the thousands of concrete cylinders made every day, there is remarkably little concrete removed from buildings because of low strength. Even though the specifications call for removal for understrength, it is difficult to enforce this clause and in most cases some compromise is made that satisfies everyone without having to remove the concrete.

"It would make more sense to me if we were able to forget strength and were able to control the deflection properties of concrete by some kind of field test or procedure. The apparent modulus of elasticity is usually unimportant, but plastic flow of concrete is a serious problem in selecting structural systems. Almost every engineer can report examples of excessive deflections due to plastic flow or shrinkage."

This strongly suggests not only that concrete strength, specified at current levels of "quality" has little relation to significant problems of buildings performance with regard to strength but that other properties, not specified, are more significant to performance. It has been suggested that the sorts of safety factors that are currently employed to obtain specified levels of strength also add unnecessarily to cost. I suggest that a proper element in the "performance concept in buildings" is avoidance of unnecessarily high costs. Here my example is taken from a discussion of an arch dam, but I feel sure similar considerations could be developed for buildings. Wengler (8) showed that it was customary to build arch dams with a safety factor of 4 as the ratio of concrete strength to design stress. He showed, for a specific example, that by reducing the concrete strength from 4800 to 2400 psi, keeping the working stress at 1200 psi, i.e., reducing the safety factor from 4 to 2, the cement content could have been reduced from 3.5 bags/cy to 2.0 and the cost of the job by 8 percent or by nearly $2 million. By keeping the originally specified concrete strength, increasing the allowable working stress from 1200 to 2400 psi, i.e., reducing the safety factor from 4 to 2 by another route, a saving of $5.4 million or 22 percent was calculated.

5. Concluding Statement

The foregoing discussion has, I trust, suggested that, with regard to the concrete used in the construction of buildings, there are substantial benefits that may be realized if one were to start with a proper consideration of the performance of the building system in going through the process of obtaining the appropriate concrete for use therein. If one were to catalog and quantify the elements of performance of the system that are needed for structural and aesthetic success, were to relate these in turn to the elements needed for satisfactory performance of concrete, in the environment of service, one could select the appropriate quality levels of materials properties, the appropriate mixture proportions and construction practices, specify as needed, and enforce the specifications. The result would be, in so far as the concrete is concerned, concrete appropriate to its intended use. Such concrete could often be made using materials not now allowed by specifications, using concrete mixtures containing smaller quantities of more costly ingredients, and often in sections of smaller dimensions. In some cases, the reverse would be the case; in these cases the structure would be made safe and satisfactory where under current practices these results are not assured. On balance there would be a general reduction in cost and a conservation of natural resources.

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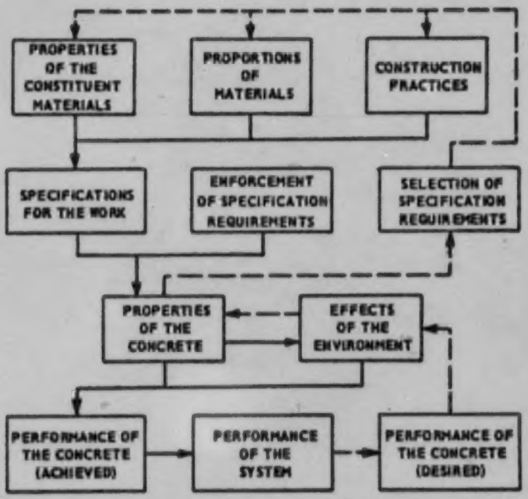

PROPERTIES OF THE CONSTITUENT MATERIALS
PROPORTIONS OF MATERIALS
CONSTRUCTION PRACTICES
SPECIFICATIONS FOR THE WORK
ENFORCEMENT OF SPECIFICATION REQUIREMENTS
SELECTION OF SPECIFICATION REQUIREMENTS
PROPERTIES OF THE CONCRETE
EFFECTS OF THE ENVIRONMENT
PERFORMANCE OF THE CONCRETE (ACHIEVED)
PERFORMANCE OF THE SYSTEM
PERFORMANCE OF THE CONCRETE (DESIRED)

Fig. 1

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

Proposed Method for Prediction of Corrosion of Reinforcement in Concrete

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A performance evaluation technique suitable for the evaluation of corrosion of reinforcement in concrete is explained. The durability of the reinforcement is a consequence of the combined effects of the environment, the properties of the concrete and the reinforcement, and of the processes caused by the external factors which affect steel and concrete. In order to be able to solve the complicated problem a systematical method of evaluation is needed. The prediction could be made with the help of a matrix which consists of a list of all the important factors affecting the corrosion of reinforcement. The evaluation can give both qualitative and quantitative information on corrosion. The evaluation technique is feasible for evaluation of the probability of corrosion of reinforcement in a defined construction. It can also give information on how a construction should be dimensioned in order to avoid corrosion of reinforcement.

On expose une technique d'évaluation de la performance appropriée pour estimer la corrosion des armatures dans le béton armé. La durabilité de l'armature est une conséquence des effets combinés du milieu, des propriétés du béton et de l'armature, et des changements causés par les facteurs externes qui affectent l'acier et le béton. Pour pouvoir résoudre ce problème compliqué, une méthode systématique d'évaluation est nécessaire. La prévision pourrait se faire à l'aide d'une matrice consistant en une liste de tous les facteurs importants qui touchent à la corrosion de l'armature. L'évaluation peut donner des informations qualitatives et quantitatives sur la corrosion. Cette technique est applicable à l'évaluation de la probabilité de corrosion de l'armature dans une construction donnée. Elle peut aussi renseigner sur la façon dont une construction devrait être dimensionnée pour éviter la corrosion de l'armature.

Key words: Concrete; corrosion; durability; material properties; morphological research; performance analysis; reinforced concrete; reinforcement.

1. General

The problem of the prediction of the durability of materials and construction is of current interest. In the past the evaluation has been based on the long-term performance. This has been possible as the development of new building products has been very slow.

The present rapid development of building products sets up new requirements on durability and especially on the evaluation of the durability. Evaluation techniques based on the behaviour of products and materials in real conditions for several years are not feasible. New evaluation techniques which make it possible to forecast the performance of various objects need to be developed.

This paper will discuss the development of a technique, which may be used in the evaluation of corrosion of reinforcement in concrete.

2. Corrosion of reinforcement in concrete

Corrosion is a phenomenon which occurs inevitably according to the laws of nature. The protection of reinforcement against corrosion is thus a problem of retarding the corrosion processes.

There has been little corrosion of reinforcement in concrete in Finland, especially for conditions where the risk of corrosion is small. Due to the present development of reinforced concrete construction the problem has attained greater actuality. As the risk of corrosion has grown, the need for prediction of the durability of reinforced construction has become ever greater.

The mechanism of corrosion of reinforcement in concrete is rather complicated. The corrosion is a result of the interaction of many environmental factors and properties of the construction. The mechanism of corrosion becomes more complicated as the affecting factors cause contradictory consequences.

The prediction of durability of reinforcement is sometimes quite difficult. There do not exist any testing methods which take the whole corrosion mechanism into consideration and it is quite unlikely that such methods will ever exist.

The knowledge of the influence of different "corrosion factors" is quite often rather limited. Although the nature of the effect may be known it is almost impossible to evaluate the extent of the influence.

The paper describes a systematical method which is in development for evaluation of the possibility of corrosion of reinforcement in concrete. The technique has been developed according to the principles of the performance analysis technique presented in paper [1][1]. The procedure of evaluation is based on methods of morphological research as given by Zwicky [2].

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[1] Figures in brackets indicate the literature references at end of this paper.

Today the method gives only qualitative information. It is, however, possible to develop the method gradually toward quantitative evaluation. Further research on the influence of different factors on corrosion is needed before a quantitative evaluation can be developed.

3. The mechanism of corrosion of reinforcement in concrete

The ability of concrete to protect the reinforcement is due to two factors. The concrete prevents the penetration of corrosive agents such as oxygen and moisture to the surface of the reinforcement. Furthermore, in highly alkaline concrete a thin protective layer is formed on the surface of the reinforcement.

The corrosion of reinforcement will occur when the protective properties of concrete are diminished. The factors which have an influence on the corrosion of reinforcement may be divided into external and internal factors [1]. The external factors are due to the environment. The internal factors may be divided into properties of the concrete, properties of the reinforcement, properties and processes of the construction and special kinds of protective treatment against corrosion of reinforcement.

3.1. Environment

The influence of the environment is most important. In order to be able to evaluate the risk and amount of corrosion, all the essential "corrosion factors" need to be known. In Table 1 the most important factors are listed. At present it is not possible to deal with each of the factors separately as there is very little quantitative information available concerning their significance on the corrosion of reinforcement.

The environment, for instance, may be classified (appendix 1) in three groups:

1. Corrosive environment
2. Medium environment
3. Neutral environment

3.2. Fresh concrete

The factors of fresh concrete which most significantly influence corrosion are:

- cement (quality)
- cement content
- aggregate
    - quality
    - grading
- water-cement ratio
- consistency
- admixtures (calcium chloride, etc.)

The cement quality has a direct influence on corrosion. The cement quality and especially the cement content influence many properties of the concrete such as porosity, water absorptivity, etc., which have an indirect influence on corrosion of reinforcement.

The passivity of the reinforcement depends on the amount of calcium hydroxide in concrete. Different cement types may produce different amounts of calcium hydroxide. The influence of cement quality on corrosion of reinforcement as found in laboratory tests is usually much greater than observed in actual constructions. The cement quality also can have an effect on corrosion of reinforcement attributed to chloride ions.

The cement content is of great importance. The minimum values recommended with regard to protection of reinforcement from corrosion vary from 235 kg/m^3 to 300 kg/m^3.

The structure of the aggregate has very little influence on the important properties of concrete if the aggregate is less porous and has a higher compressive strength than the cement paste.

The porosity of the aggregates must be considered when the possibilities of corrosion are determined. Grading as well as the shape of the aggregate have an influence on important properties of the concrete which in turn can have an effect on corrosion of reinforcement. Sometimes the aggregate may also be chemically harmful to the concrete.

The water-cement ratio is an important factor, which determines the properties of the concrete. It also has a very significant influence on corrosion of reinforcement, as the risk of corrosion increases when the water-cement ratio increases.

Calcium chloride is a very commonly used additive. The chlorides have a reducing effect on the passivity of reinforcement. In normally reinforced concrete constructions an addition of calcium chloride may not be harmful if the amount is smaller than 2 % by weight of cement. In prestressed concrete structures, however, addition of calcium chloride is not desirable.

3.3. Concrete construction

Denseness of concrete is a very decisive factor in corrosion of reinforcement in concrete. A dense concrete prevents the penetration of aggresive substances to the reinforcement. it also makes it difficult for water and oxygen to migrate in the concrete. Denseness of concrete is thus the most decisive factor in the corrosion of reinforcement.

The carbonation of concrete reduces the alkalinity of concrete. This endangers the passivity of reinforcement. If the carbonated concrete layer reaches the reinforcement, corrosion of the reinforcement is very probable.

Cracks in concrete may have a harmful effect on reinforcement as they favour the penetration of moisture, oxygen and aggresive substances to the reinforcement. The allowable crack width with regard to corrosion of reinforcement has been widely discussed. Definitive conclusions may not be made as the nature of the corrosion cell caused by a crack may vary, e.g., the reinforcement may corrode at the crack or beside the crack.

The depth of the concrete cover has an influence on corrosion of reinforcement. It must always be taken into consideration in correlation with the denseness of the concrete. A thin, dense concrete cover protects the reinforcement better than a thick, permeable concrete cover.

The quality of reinforcement may have an influence on corrosion of reinforcement. The structure of steel, composition of steel, initial stresses in the reinforcement, bar diameter etc. are factors which have an influence on the risk of corrosion and especially on the dangerous effects of corrosion.

3.4. Protection against corrosion of reinforcement

When the risk of corrosion of reinforcement is high and the properties of the concrete and concrete construction are not sufficient to eliminate this risk, special protective treatments may be used.

Inhibitors may be used as additives in the concrete. They reduce the processes of the electrodes of the corrosion cell. The weak point in the use of inhibitors is the fact that they are consumed and may loose their effectiveness with time.

Cathodic protection is used to make the reinforcement immune to corrosion. An artificialanode is installed in the construction. If all the reinforcement is not connected in the electric circuit the results may be very disasterous as stray current will cause the unconnected reinforcement to corrode rapidly.

Protective layers on the reinforcement may be used to eliminate the risk of corrosion. The use of protective layers must be considered carefully as they eliminate one of the best protections, the passivating influence of cement.

The protective layers may be metallic or non-metallic. The surface treatment of reinforcement may also have an effect on bond between the reinforcement and concrete.

4. Evaluation of corrosion

As already has been stated the corrosion of reinforcement is a consequence of the combined effect of the environment, properties of the construction, including properties of hardened concrete and reinforcement, and processes caused by external factors on steel and concrete.

In order to be able to estimate the magnitude of corrosion of reinforcement we must know all the factors which are of importance. We should also understand how these factors act and to what extent. That is why there is a need for a systematical evaluation procedure.

The method of morphological research is an approach which can be used also in the prediction of corrosion of reinforcement. This method has been applied successfully in technological forecasting in search for new solutions to different kinds of problems. The procedure is as follows:

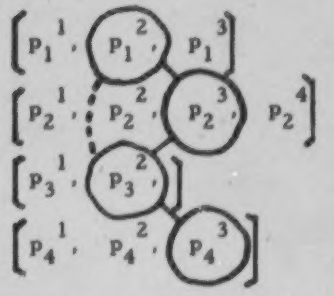
At first the problem must be defined adequately. When this is done, all factors essential for the problem must be clarified.

This is very important because only then we can be sure that all possible solutions of the problem can be brought under examination.

As the second step we list all factors one below the other, so that they form a column. After that, each factor is given all the possible independent values it can have in reality (horizontal row). The problem thus gets a form of horizontal matrices lying one below the other. The number of matrices is equal to that of the factors, which describe the problem.

	Values
Factor	$p_1^1, p_1^2, p_1^3, \dots p_1^{k \cdot 1}$
Factor	$p_2^1, p_2^2, p_2^3, \dots p_2^{k \cdot 2}$
Factor	$p_n^1, p_n^2, p_n^3, \dots p_n^{k \cdot n}$

If one element is encircled in each matrix and these circles are connected with each others a chain is formed, which describes one possible solution of the problem.


p_1^1, p_1^2, p_1^3
p_2^1, p_2^2, p_2^3, p_2^4
p_3^1, p_3^2
p_4^1, p_4^2, p_4^3

It is also possible that the values of one or several factors are equal to zero. They do not have any influence in that special case and that is why they are left out of the chain (broken line).

This kind of a systematical procedure could be of practical help in the evaluation of corrosion of reinforcement as it gives a good picture of the real situation. It reveals the values of various "corrosion factors" and gives a possibility of judging how a certain combination of factors affects the corrosion.

For practical use the method should be developed further in order to make it possible to "calculate" the corrosion risk. Then every factor is given a numerical value which corresponds to its relative significance. Within every factor this value can be divided further in smaller parts, so that every parameter of each factor has a numerical value, which proportinates its influence on corrosion of reinforcement. When the values of the encircled parameters are counted up, they yield a figure which relative to the possibilities of corrosion. The values of the factors and their parameters have to be chosen in a way, which gives trustworthy results.

The degree of corrosion of reinforcement may be divided into three categories:

1) corrosion is very evident and can be dangerous to the construction
2) corrosion is possible
3) the probability of corrosion is very small.

Then the limit values between the various categories have to be chosen so that they give a correct picture of the situation.

Today this kind of evaluation can give reliable information only when the probability of corrosion is very great or very small. (The sum of the values of the parameters is outside the limit values). In many cases the calculation leads between these limit values (second degree), where it is difficult to predict the possibility of corrosion of reinforcement. In spite of that the morphological evaluation system (without calculations) can be of great help. When one goes through the chain formed by the encircled parameters, one can base the judgement on the actual combination of these parameters. There can be a situation where a single factor determines the risk of corrosion. If this factor has a value that is on the "safe" side there is no need for further study and the other factors of the matrix can be neglected.

It is evident that this kind of corrosion evaluation cannot solve the total problem. There are also many difficulties in the application of the method. It is for instance very laborious to study the relative significance of every factor and the connection between various values of the factors and the corrosion of reinforcement. The number of tests needed for this evaluation is enormous and in studying the effect of one factor all the other factors should be kept constant. That is why we have to concentrate our studies on the effect of some of the main factors which can be regarded most important in corrosion of reinforcement. Thus the calculation of the possibilities of corrosion could be based only on these main factors and the major matrix which includes all corrosion factors could serve as a checklist so that we can ascertain that all possibilities are included in the evaluation. This is very important as there can be situations where the corrosion of reinforcement is due to an "unexpected" factor and especially to a certain combination of various factors.

Table 1 is an example of a morphological system which can be used in the evaluation of corrosion of reinforcement in concrete. It is only a draft. Also it does not take any stand in regard to the significance of various factors in the corrosion process.

5. Conclusions

The above described systematized procedure for the evaluation of the risk of corrosion of reinforcement in concrete has been developed according to the principles of the performance analysis technique which is described in the paper "Performance Analysis" [1], which has also been prepared for the symposium.

The method described above can be used in evaluation of the probability of corrosion of reinforcement in a known construction. It can also give information on how a construction should be dimensioned in order to avoid corrosion of reinforcement.

At the present the method is rather qualitative. In the future it may be possible to make the evaluation more quantitative and more accurate. This needs rather extensive research work on the mechanism of corrosion and the influence of different "corrosion factors".

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Table 1. A morphological model for the prediction of corrosion of reinforcement in concrete

Environment	Air:	Type of climate	Rural	Urban	Inland	Sea	Industrial	Factory
		Relative humidity, %	50	60	70	80	90	100
		Temperature, °C	10	20	30	40	50	60
		°F	50	68	86	104	122	140
		Aggressive gases	-	-	-	-	-	-
		Other aggressive agents	-	-	-	-	-	-
	Water:	Water quality	River	Sea		Rain	Waste	Industrial
		Temperature, °C						
		°F						
		Aggressive agents						
	Soil:	Soil type						
		Permeability						
		Aggressive agents						
		Backfill material						
Concrete	Aggregate:	Material						
		Grading						
	Cement:	Quality						
		Content, kg/m^3	200	250	300	400	500	600
		lb/yd^3	335	420	505	670	840	1000
	Water:	Impurities						
	Additives							
	Water-cement ratio w/c		0.4	0.5	0.6	0.7	0.8	0.9
	Consistency, VB°		2	3	5	7	10	10
Reinforcement	Bar Diameter, mm		4	8	15	20	25	25
	in.		0.15	0.30	0.60	0.75	1.0	1.0
	Bar quality							
	Steel quality							
Construction	Width, mm							
	in.							
	Depth of concrete cover, mm		10	20	30	40	50	50
	in.		0.40	0.75	1.20	1.60	2.00	2.00
	Permeability							
	Carbonation, mm		5	10	20	30	40	50
	in.		0.20	0.40	0.75	1.20	1.60	2.00
	Other corrosion							
	Erosion, mm							
	in.							
	Crack width, mm		0.1	0.2	0.3	0.4	0.5	0.5
	in.		0.04	0.08	0.12	0.16	0.20	0.20
Protection	Inhibitor							
	Cathodic protection							
	Protective layer on reinforcement							
	-"- on concrete							

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The Performance Concept Applied to Building Materials - an Unattainable Ideal

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The performance concept is the only logical basis for building regulations for the selection of building systems and for the whole design process, which does not implicitly restrict the designer on his choice of materials and form. Nevertheless, experience has shown that it remains an impractical ideal when one attempts to apply the concept to specification and control of materials. This is probably most evident for concrete and for plastics, which two materials are discussed in this paper.

There is no dearth of tests for concrete which may be used to assess the performance of the material in various ways, but there remain many important properties for which it is impossible to specify rational limits for the properties measured. There are also many tests which produce results, but these measures are of little value because they are obtained in conditions which are too far removed from the practical conditions in which the material will be used. Shrinkage and standard crushing tests for concrete are considered as examples of these viewpoints and yet might appear to be successful and valid applications of the performance approach.

Plastics may also be characterized by a variety of tests relating to many chemical and physical properties, and being manufactured to meet certain of these properties would also appear to offer opportunity for control by specifications based upon performance tests. However, the functions most frequently required of plastics in building application include aesthetics, weathering, and fire resistance; and the development of performance specifications to encompass such properties is shown to encounter problems at every step.

In view of these and other examples to be cited, it is proposed that there should be a widespread return to prescription specifications to complement quality and valid performance property testing. The tests needed to police a prescription specification are usually simpler and quicker to carry out than performance tests and are equally satisfactory for control of uniformity.

La notion de performance est l'unique base logique pour les règlements de la construction dans la sélection des systèmes de construction et pour toutes les opérations d'un projet, qui n'impose pas au projeteur implicitement une restriction dans le choix des matériaux et des formes. Néanmoins l'expérience a montré que le concept demeure un idéal impraticable quand on essaie de l'appliquer à la spécification et au contrôle des matériaux. Ceci est probablement évident, avant tout, pour le béton et les plastiques, 2 matériaux qui sont abordés dans cette communication.

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[1] Assistant Chief of Division and Principal Research Scientist, respectively

Les essais pour le béton ne manquent pas, ils peuvent être utilisés pour évaluer la performance du matériau de bien des façons, mais de nombreuses propriétés importantes demeurent pour lesquelles il est impossible d'établir des limites rationnelles des caractéristiques mesurées. Il y a aussi de nombreux essais qui produisent des résultats, mais ces mesures sont de peu de valeur car elles sont obtenues dans des conditions beaucoup trop éloignées des conditions pratiques dans lesquelles le matériau sera utilisé. Des essais de fluage et d'écrasement normalisé du béton sont, de ce point de vue, donnés en exemple, et pourtant, ils peuvent apparaître comme des applications réussies et valables du principe de performance.

Les plastiques peuvent aussi être caractérisés par divers essais, se rapportant à de nombreuses propriétés chimiques et physiques. Comme ils sont fabriqués pour satisfaire certaines de ces propriétés, ils devraient aussi se prêter à un contrôle par des spécifications fondées sur des essais de performance. Toutefois, les fonctions le plus souvent requises des plastiques utilisés dans la construction comprennent la satisfaction esthétique, la tenue aux conditions atmosphériques, la tenue au feu; or le développement de spécifications de performance qui tiennent compte de ces caractéristiques se heurte à des problèmes continuels.

Compte tenu de ces exemples et d'autres à inclure, on propose un retour général à la prescription de spécifications en vue de compléter les essais de qualité et de performance requise des caractéristiques. Les vérifications nécessaires pour régler les spécifications prescrites sont en général plus simples et plus rapides que les essais de performance et sont tout autant satisfaisantes pour l'obtention de résultats uniformes.

Key words: Building materials; concrete; functions in building; material prescriptions; performance concept; plastics; property tests.

1. Introduction

It may fairly be claimed that the ideas implicit in the term "performance concept" are well enough understood to need no further exposition. Generally this is true, but as the authors wish to present an adverse criticism of the performance concept in one of its many applications it seems appropriate that they should define the system which they are criticizing.

The performance concept requires firstly some defined quantitative levels of performance for a building, its components, elements and materials. Ideally, these should cover every aspect from which the building can be judged, including aesthetic as well as technical properties such as strength, fire resistance, durability, and acoustic behaviour. Quantitative measurement of aesthetics is not yet possible and the idea itself would be an anathema to many, but this is not the point at issue here.

The advantage of the performance approach is that it should give the designer and constructor much greater freedom in their choice of materials and methods of construction, and should also leave no doubt that the users' requirements will be met.

Secondly, the performance approach requires reliable methods of test for each property by which performance is specified, or alternatively a test for which the quantitative

result has a clear correlation with the property specified.

The question which is asked is whether these two conditions can be met, whether it is possible to define quantitatively all the necessary properties of a material, and whether there exist reliable methods of test which can measure the properties. It is contended that neither of these conditions exists to any useful extent, that in many cases they are never likely to exist, and that the instances in which they appear to exist are deceptive.

The performance approach to design of buildings is probably a sound framework for teaching, and by which codes of practice and building regulations should be guided, but it is virtually impossible to apply it rigorously to the specification and control of building materials.

In what follows this thesis will be supported by an examination of the situation in relation to structural concrete and to plastics. As space is inevitably limited an arbitrary decision has been made to deal in some depth with these two types of material rather than to deal perhaps too briefly with as many materials as possible. It is confidently felt, however, that similar, but not identical arguments can be presented about other materials.

2. Concrete

In buildings, concrete requires durability and impermeability on external surfaces; on all surfaces, especially floors, it requires surface hardness; in walls it requires acoustic insulation; in structural members it requires fire resistance, strength, and damping capacity, and overall thermal capacity is desirable. Many of these properties are influenced by the degree to which the material is cracked, and therefore crack resistance becomes an important property.

The tests for concrete and its components now fill a large volume (U.S. Corp. of Engineers Handbook) so that at first sight it seems that there is an almost ideal situation for the use of the performance approach to specification and control, but in fact whatever performance is required it is only rarely that anything other than crushing strength is specified. There have been occasions in Australia in which the tensile splitting strength or the drying shrinkage have been specified, but these have usually been abandoned.

There are undoubtedly several reasons why this practice has evolved. Provision of a wide range of test facilities is expensive, and they are frequently costly and time-consuming to operate; the crushing test was well established before other properties were recognized as important. However, apart from these economic reasons it is also true that in many cases there are still no suitable tests, and in others there are tests which it is claimed measure the property in question but for which there are no recognized limits of acceptability.

In slab-on-ground construction for houses or factories crushing strength of concrete is irrelevant, but surface hardness is vital. Surface hardness or the absence of a weaker loose surface are essential for vertical faces of concrete to be painted or rendered. There is no recognized test for surface hardness or abrasion, and one survey shows that methods which have been tried can give completely contradictory results (International Study Committee for Wear (1)[2]. Undoubtedly there is a broad correlation between crushing strength and abrasion resistance, but it is quite possible to have good crushing strength and a poor surface through inadequate curing.

Even in regard to mechanical properties it is rare that anything approaching a genuine performance test is attempted. The flexural strength of reinforced concrete members is directly dependent on the strength of the steel and the accuracy of its location, and only to a minor degree on concrete properties, and the same holds true for deflection. It has been shown by Blakey (2) that with one percent of tensile reinforcement a drop of fifty percent in the concrete strength will produce a drop of only about ten percent in the flexural strength of the member. It would seem that a much more useful control than the current practice of cylinder testing would be to determine the actual reinforcement position with a series of measurements with a covermeter immediately after screeding off.

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[2] Figures in brackets indicate the literature references at end of this paper.

Perhaps the most important requirement of a very great amount of the concrete that is placed is just uniformity, and while the crushing test does provide a measure of uniformity this could be measured in many other ways without waiting 28 days, as required by the standard test.

Because the essential need is uniformity, and because so much of the required performance of the concrete, such as surface hardness and some aspects of durability has not been quantified, or as for shrinkage there are no agreed limits, it has for some time been advocated by Blakey (2) that there should be a return to prescription specifications with emphasis given to content of cement, water, and air. All these can be checked before the concrete is set. That this is becoming more widely appreciated is apparent from the proposed redraft of the American Concrete Institute Code for Structural Concrete (ACI 318-66) where maximum water/cement ratios and minimum cement contents have been specified to ensure durability.

Even when the concrete crushing strength may be critical, as in columns, piles, and prestressed units, the standard crushing test cannot be regarded as a true performance test. It has been shown in a review of Lewis (3) that the ratio of the crushing strength of cores cut from concrete members to that of the strength of standard cylinders is always less than unity. However, the value of the ratio varies with the strength of concrete, the size of the specimen, and composition of cement, and is only slightly affected by the cutting action itself. It is, in fact, not possible to determine the compressive strength of a concrete member without relying on implicit or explicit empirical correlations.

3. Plastics

Upon cursory consideration plastics materials may appear viable for specification in terms of the performance concept. Indeed, the status of plastics materials is as contemporary products in the vanguard of innovative developments for building requiring a change from the traditional approach of assessing suitability in order to exploit their full potential. Specification in terms of material analysis is extremely difficult because an infinite number of variations is possible in the chemical makeup of apparently the one base polymer, and the path to producing this polymer is not detectable in the finished product. Minor constituents, generally termed catalysts, accelerators, or hardeners, and minor changes in proportions will control important chemical structure parameters such as chain length, chain branching, and crosslinking, while conditions during production will influence important trace impurities such as are caused by oxidation or thermal degradation. Most of these parameters cannot be conveniently measured. Furthermore, the plastics materials used in buildings are generally compounded from polymers and the content, chemical type, and degree of dispersion of other constituents in the finished product are also difficult to determine.

Plastics materials are therefore characterized by phenomenological properties such as viscosity, hardness, softening point, and density, or processing requirements such as moulding temperature and curing rate or resistance to some environmental torture test.

Plastics materials are tailor made to conform to certain of these property requirements, and specification in terms of the performance concept would only require the substitution of performance tests for the quality tests now utilized. Unfortunately, herein lies some inherently insoluble problems.

Plastics are used in buildings in a variety of applications with a consequent proliferation of requirements. Surfacings to internal walls require mechanical properties of tear resistance; aesthetic properties of colour, texture, pattern, and gloss; cleanliness properties of resistance to staining and grime accumulation; and durability so as to retain these properties. Furthermore they must be safe if subjected to fire, particularly in that the rate of spread of flame must not be excessive. External claddings also impose as major requirements the three general properties of aesthetics, durability (including corrosion resistance), and fire resistance. Variants on these properties are also required for plastics plumbing - aesthetics in the ability to be moulded to certain shapes and to be cleaned, durability in resistance to handling aggressive fluids and thermal change, and fire resistance, particularly in relation to flame spread, toxic gases, and smoke production because pipes and ducts often provide the only path through fire breaks such as walls and floors in large buildings.

Accepting the logical steps of Achenbach (4) in developing performance specifications, problems are encountered at every step. The first step, identifying component performance, is difficult because the important characteristics of the performance of plastics components happens to involve aesthetics, durability, and fire resistance, and none of these are easily identified in objective terms. Leaving aside aesthetics per se, durability of plastics must often be defined in terms of change of aesthetic properties, only some of which such as colour and gloss can be measured. For instance, panels of glass-reinforced polyesters become unacceptable after weathering resulting from accumulation of grime, glass prominence, and discoloration rather than by loss of objective properties of flexural strength or impact resistance. With many plastics materials the characteristics that identify weathering performance are not predictable. Rigid plastics foams with high thermal resistance and low heat capacity when used as substrates cause increased extremes of surface temperatures, which may lead to more rapid degradation at the surface by chemical reaction (vinyl coatings) or physical strain (roofing membranes), and it has required field failures to uncover these deleterious aspects. A compromise with other performance characteristics such as resistance to heat transfer is required in such applications of rigid plastics foams, and this is difficult to define because it will depend upon environmental factors. The important characteristics of the behavior of plastics in fires have been generally identified by Saunders (5) and it is with Achenbach's second step that difficulties arise.

The second step in the performance specification is to define the field conditions. Only a feeble attempt can be made at this definition in objective and comprehensive terms in relation to durability of plastics, because the climatic factors responsible for weathering are not yet available in terms applicable to the processes of deterioration of plastics. A review by Martin (6) indicates that solar radiation is required in terms of frequency of occurrence of intensity levels and of wavelength bands to which specific plastics are most sensitive. Temperature is required in terms of body temperature of the plastics component, which varies considerably from ambient air temperature according to factors such as heat capacity and solar absorptivity of the plastics component. Even the moisture condition of the environment cannot be accounted for by a simple objective measurement such as annual rainfall. The situation is further complicated because the mere statement of boundary conditions is not an adequate definition of conditions relating to weathering. Threshold values occur below which an environmental factor may have no effect, and above which the effect increases in a non-linear manner. Polyvinylchloride will not thermally degrade at temperatures below 65°C, but dehydrochlorination proceeds at a continually increasing rate at higher temperatures in air. Photochemical reactions may also exhibit an induction period below a threshold value of radiation intensity and furthermore, the extent of reaction may depend upon both total exposure and the intensity of the exposure to solar radiation. Neither a statement upon maximum intensity of radiation received nor duration of exposure to the radiation will generally suffice to adequately define the field condition.

When the condition of fire is considered, the attempt at definition in quantitative terms is very complex for all combustible materials, and particularly for plastics where a history of experience is not available following the many new innovations with these materials. There is some evidence that in large fires some plastics partly distil; this reduces temperatures but increases spread of flame, and may also give rise to greater amounts of toxic gases and smoke than with other materials. A recent survey by Martin (7) indicates that the influence of many conditions such as heat, ventilation, surface orientation, and object geometry is not understood and hence it is not possible to define field conditions in the optimum manner. Environmental conditions are extremely important in these cases, because conditions favoring pyrolysis may yield products completely different from those given by the same plastics when conditions favor combustion. Thus many flame retardants suppress combustion, and this suppression may directly cause the production of more smoke because the pyrolysis reaction may yield more smoke than the combustion reaction. Similarly, pyrolysis may give rise to toxic gases as in the case for production of isocyanates from some polyurethanes, which are not produced in the oxidative degradation associated with combustion. The precise definition of conditions for changeover of pyrolysis to combustion is slowly being developed for the commonly used plastics, but this relates only to oxygen content of the atmosphere with no consideration of preheat; not enough information is yet available for application in performance specifications.

The third step, to identify the material properties that determine performance characteristics is obviously a corollary of identifying the latter, and does not need further elaboration to the general thesis that there is at this stage insufficient knowledge for the comprehensive specification of plastics materials in terms of performance. It is the fourth step, the development of test procedures, which demands concern because the temptation exists to adopt quality tests as performance tests. There are many quality tests used to control products made from plastics materials but few if any of these tests are applicable to performance. A particular problem relating to weathering is the need to contract the time scale in any performance test. This is usually done by increasing the intensity of the weathering factor in an artificial environment to which the material is exposed, and assuming a superposition of the factor with time. The work of Ferry (8) has shown the rules which must be met for this approach to be valid, but the validity has not been explored for the many heat aging and artificial weathering tests applied to plastics. Thus the results of these tests cannot be applied to performance in the sense as to the relative duration that the material will continue to function satisfactorily. The tests may be devised so that specific changes due to weathering are reproduced, but the relation between test conditions and rate of change are not understood in quantitative terms. When multiple manifestitations of change are studied the influence of test conditions is often not even understood in qualitative terms. Thus one form of surface whitening of PVC claddings can be reproduced by exposure to xenon-arc irradiation at low surface temperatures, but in attempts to combine the thermal degradation of PVC with the photo-degradation the artificial chamber does not reproduce what happens in practice. Similarly, the xenon-arc irradiation will reproduce the yellowing of glass-reinforced polyester resins which occurs upon natural exposure, but attempts to combine the moisture hazard in the artificial environment have not been successful in reproducing the glass prominence and resin erosion that occur outdoors. The natural changes attributed to moisture hazard can be reproduced by exposure in boiling water, and this condition is widely used as a quality control test. However, acceptance of this as a performance test is misleading because quantitative relations to the field condition are not established, i.e. the superposition of increased temperature for time of wetness has not been validated. The danger is, of course, that these matters of valid acceleration of a degrading influence are often overlooked when one happens to find a test condition, a material and a change in the material that reproduces the field case. The specific nature of the combination and the rules for extrapolation to different materials or changes are not realized.

This situation of a proliferation of tests but lack of relation between the test and the field condition also applies to the property of fire resistance of plastics. Minor variations in the condition of fire tests concerning specimen size, specimen geometry, amount of preheat, degree of ventilation, or source of ignition have been found to greatly influence the results. Hilado (9) has discussed some 30 tests in use in the United States for assessing the flammability characteristics of cellular plastics, and gives some indication of the different ranking of a series of materials by the different tests. The problem is the difficulty of studying the field case and the danger is that any one of these tests may be set up as a performance test without the complete understanding of its limitations. Lindeman (10) discusses more than 200 recent patents on fire retardants for polystyrene, and invariably the method of test was not stated or was the simple ignition of a horizontal bar with no preheat. This test has very limited meaning, but because it is simple it is widely used and accepted by patent authorities. Some of the retardants have either none or deleterious effects when evaluated under more stringent conditions (Martin (7)), the widely used simple test being deceptive when the results are extrapolated to different conditions. On the other hand, a large scale test commonly known as the Steiner tunnel (25 ft long) is the only one standardized and has assumed importance beyond the field for which it was devised. Some authorities have considered using this test in regulations for plastics floor coverings, irrespective of the fact that the specimen is attached to the ceiling of the tunnel. It is generally agreed by responsible research workers that meaningful test methods to evaluate the fire resistance of plastics are not yet defined. The trend in both the United States (Society of Plastics Industries) and England (Rubber and Plastics Research Association) is to resort to near full-scale burns of experimental buildings or rooms and corridors furnished with the materials under study, so that a further understanding of the field condition and the relation of more convenient tests to the field situation can be established. The performance concept will play an important role as a policy to guide these developments, but it is unlikely that plastics materials will be controlled by valid performance tests in the foreseeable future.

Even with the establishment of useful tests the final steps in developing performance specifications of collating test data, standardizing procedures, and fixing required performance levels will pose many difficulties. The fact that many existing specification tests are specific to certain materials often facilitates the writing of a standard procedure. Elastomeric sealants based upon polysulphides and silicones perform the same function but differences in curing rates, types of primers needed for the same substrate, and rheological response when placed under strain make it difficult to devise common performance tests. The adoption of fair levels of acceptance must be based upon field observations, but with the rapid changes in formulations of plastics such relevant data are scarce. It has been said that feedback of field studies in plastics is always pessimistic because current improved formulations are excluded. While this may be a doubtful argument it does highlight the difficulty of establishing meaningful performance levels.

4. Conclusion

Two types of material have been dealt with at some length, but as stated earlier it is claimed that for other materials arguments can be put forward which parallel those which have been presented. For example most of what has been said for plastics applies equally to paints. Again, for renderings, what performance is required? Perhaps hardness and adhesion, but at what quantitative level? Is a test of adhesion in tension a guide to adhesion in shear?

Too often the existence of a physical test which may be suitable for quality control has been accepted as a performance test without the correlation with the important parameters in field performance ever having been established. For any one parameter it is nearly always impossible to set a single, unique limit of acceptability because in practice the acceptable limit depends on the interaction of so many factors.

Even if it were admitted, in the abstract, that these difficulties could be overcome by continued research, it would seem almost certain that the resulting sequence of tests would be much too complex for practical implementation. To say the least, a wholesale abandonment of prescription or material type specifications is premature.

Finally it is of interest to note that the directives for assessing the merits of component innovations according to the Agrément approvals scheme in Europe are based upon a variety of methods. Outdoor exposure trials, field examples, material descriptions, quality tests, and some performance tests are taken into account and even then a knowledge and experience of the building industry are necessary before an appraisal can be stated. The performance concept is meant to provide freedom to designers from having to name materials, but since our knowledge of the comprehensive function of building components in relation to influence of environment and pertinent generalized material properties is insufficient, it appears that all the means available will be required to enable designers to specify and achieve the best results in building.

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EVALUATION OF PERFORMANCE OF MATERIALS PERFORMANCE AND DIMENSIONAL STABILITY OF RESIN BINDERS

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Although there are standard methods for evaluating the performance of composites based upon traditional binders such as hydraulic or bituminous binders, we have no methods for evaluating binders and composites made of resin.

The author describes some tests capable of being used and possibly standardized, among which is the dimensional stability measurement test. This test could be adapted to resin binders and composites on one hand, and on the other hand, adapted to large dimensional elements both prefabricated and constructed on site.

Bien qu'il existe des méthodes standardisées pour évaluer les performances des composites, basées sur les matériaux traditionnels tels que les liants hydrauliques et bitumineux, nous ne possédons pas de méthodes pour apprécier les liants et composites à base de résine.

L'auteur décrit quelques essais susceptibles d'être utilisés et éventuellement normalisés, parmi lesquels figure la mesure de stabilité dimensionnelle. Cet essai pourrait être adapté aux liants résineux et composites d'une part, et d'autre part, ajusté aux grands éléments dimensionnels préfabriqués et assemblés sur chantier.

Chapters :

1. Statement of the problem.
2. Resin binders.
3. Fillers.
4. Composites.
5. Elements.

Key Words: Adhesion; composites; dimensional stability test; fillers; performance; resin binders.

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1. STATEMENT OF THE PROBLEM.

For more than 10 years, the construction industry has used a new type of binder [1][1] [2] . Thus, added to hydraulic or organic binders (the latter with low molecular weight) are thermosetting binders which develop a bi or tri-dimensional network during the period of solidification.

Epoxy, ester, isocynate and acrilic formulations furnish basic structures for the formation of certain types of binders which are called resin binders. Epoxy binders are most frequently used in civil engineering because of their well-known strength of adhesion to several different types of substrates, particularly to concrete and structural steel.[3]

Polyurethane and acrylic resins are recent developments in the field of binders and have not been thoroughly field tested. Polyester resins are used mostly in prefabrication where work and its environment can be controlled with precision. Application of resins as binder for composite materials constitute an in situ extension of techniques tested in the laboratory. Resins show great sensitivity to the environment conditions in which they are prepared (temperature, humidity, nature and surface state of the substrates, batching of components). [4] .

In this paper, we will consider non-standardized methods presently used in forecast of performance and in the evaluation of composition. It is essential to devise quick methods for evaluating the performance of binders and mortars which cure under the actual variable conditions at construction locations. Let us suppose that the use of a binder or a composite used in this binder perfectly elaborated, takes place with use of perfectly elaborated technique. It is obvious that such a procedure should involve methods of evaluation which allow for a change in composition as required by particular environmental conditions, and for the control methods for quality of application.

These measurements and control methods ideally should give useful data on the actual and the long-term behavior of the composite. A proposed technique for a composite evaluation which involves the variations in ultimate application cannot be considered satisfactory if it does not contain means of controlling the parameters on which the performance and durability depend. This concept has been in use for several decades in large applications of traditional composites, although builders have a long experience with these materials. This concept should be applied in cases where composites based on resin binders are used; for example, highly technical products which are sensitive to job conditions which act directly on the kinetic energy available for acceleration of the reaction of solidification.

2. BINDERS.

2.1 Reactivity.

A characteristic common to resin binders is their tendancy to solidifiy at various rates in the varying environmental conditions at the construction site. According to the resin's class and composition, it is possible to regulate the kinetics of solidification under given conditions within a broad range. Once the optimum proportion of hardeners, catalysts, accelerators and additives, is determined; it is advisable to adhere to these proportions and to precisely define the binder's reactivity. It is important to know the rate of change from the liquid to the solid state because the rate affects the application procedure. The following method operating under quasi-adiabatic conditions is often used [5]: 100 gr. of binder (resin, hardener and additives) is mixed under vacuum (Fig. 1) at room temperature and put in an insulated chamber (foam block made of polystyrene or polystyrene-polyurethane). The temperature rises as a function of time and is measured with the aid of a thermocouple. When the temperature reaches 50°C, the polymerization of the binder advances to a point where it is no longer workable. This is the limit of "workability". The length of time it takes to reach this temperature may be considered as the pot life of the binder (t at 50°C) (Fig. 1), t_{max} is the time necessary to reach the maximum temperature, T_{max}, of the reaction.

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[1] Figures in brackets indicate the literature references at end of this paper.

The ratio t_{max}/t_{50} characterizes the limit of workability. We note that when a binder is kept in a 20 to 25 liter container, for example, coagulation starts under quasi-adiabatic conditions. Thus, its reactivity measured at the highest reaction rate is similar to that when it is in multi-liter container. The homogeneity of the mix is important, and it is recommended that it be prepared with a high speed mechanical mixer under vacuum. The viscosity is very sensitive to temperature variation and increases as its components intermingle and make contact. Moreover, the non-Newtonian nature of the resin should be noted as well as the development of this characteristic with temperature. A rotating viscometer is used to measure the viscosity. It is recommended that the reactivity curve T versus t for a material under development should conform in form with that in Figure 1.

2.2 Mechanical Characteristics.

Although binders are rarely applied without loads [6] [7] , it is useful to be acquainted with the performance in such particulars as:

a. Tensile strength at -30, -15, 0, 10, 23, 45, 60°C.
b. Nature of failure for tests in a.
c. Tear strength (ASTM - D1004) from -20 to 23°C.

A 750 cm^3 mix was prepared as indicated in 2.1 and poured on a horizontal glass sheet coated with a stripping agent. Adhesive bands on the glass formed a tray 50 x 50 cm. This resulted in a sheet 3 mm thick. Any air holes formed on the surface during casting can be eliminated by sweeping in hot air or a gas flame if the composition does not contain volatile inflammable solvents.

After 24 hours in a standard atmosphere (ISO R-291), 21 shear specimens (ASTM D638) and 6 specimens for tear strength (ASTM D1004) were prepared. For materials whose hardness (Shore C) is less than 80, tests specimens were prepared with a punch. For materials with hardness greater than 80, micro-fissures may occur during the punching, and for these, it is advisable to use a sharp cutting tool.

The presence of cracks, even if microscopic, reduces the material's performance qualities, particularly the shear strength [8] . Prior to mechanical testing, the test specimens should be kept at room temperature for 6 days (ISO R-291). Shear tests on shear and tear specimens should be performed at the rate of 50 mm/minute for materials whose hardness is less than Shore C-80, and at the speed of 5 mm/minute for stiffer materials. These rules are empirical, but it is imperative to establish international uniformity of test methods.

2.3 Effect of Post-Polymerization.

Systems cross linking under storage at atmospheric pressure and room temperature are generally under-polymerized when first made. Post-polymerization occurs spontaneously during a period of several months and the process is accelerated in proportion with the energy that is available for activating it (elevation of temperature, solar or nuclear rays). Cross linking of links that are still reactive lead to a volume contraction called post-polymerization, and to the reduction of rupture in shearing and an eventual weakening of tear strength. In order to evaluate this effect on any given system, it is advisable to store the prepared specimens as indicated in Section 2.2 for 7 days at 80°C in a ventilated oven. This period of accelerated post-polymerization extends beyond the seventh day after casting of the sheet (one day of solidification plus 6 days of aging at normal conditions). It is useful for compositions not yet studied to record the evolution of hardness and shear strength during the period of post-polymerization as a function of time of reaction. (Fig. 3). For compositions used for their property of flexibility (skins), it is important to assure the maintenance of this flexibility (i) at low temperatures, (ii) at low temperatures after post-polymerization, and (iii) under dynamic motion. The value of ductility is significant in this instance.

2.4 Dimensional Stability.

As has been stated, the binder's cross linking during solidification and then during post-polymerization, promotes volume contraction and eventual loss of weight if the composition contains solvents of low vapor pressure. DEGEIMBRE has made a thorough study of this subject in the last 3 years [9] [10] [11] . Volume contraction in the first phase can be measured during the study of the binder's reactivity. The method described in Volume N° 327 - 1962 ASTM Special Technical Publication, pp. 40-50, by ROSEN and FORNOF can be used. Contraction in the first phase of cross linkage (24 hours) is about 2 to 10 % according to the type of binders. Sufficient precision can be obtained in the measurement by operating with a volume of 10 cm^3 evaluated to 0,1 percent. Duplicate measurement after solidification gives valuable results; but measurement of volume in the liquid phase should be done with caution (variation of temperature). However, contraction during the first phase of solidification is not always harmful to the behaviour of the binder as long as it is not accompanied by formation of internal stress resulting from restrained contraction. In a thin layer, the contraction is restrained by the adherence of the layer to the substrate [12]. In the case of mortars, the displacement of aggregate granules does not normally restrain the development of contraction. However, under high loads, granules enter into contact and restrain contraction; thus, internal stresses leading to microcracking are noted. This results in a reduction of mechanical properties under static and dynamic conditions. [16]

Contraction can be divided into 3 sections (Fig. 4). Chemical contraction does not produce internal forces until the moment of network formation (t_e). Thermal contraction depends on the value, T_{max}, and on the thermal expansion coefficient. Finally, post-polymerization contraction is responsible for a fraction of the total contraction. For resin mortars capable of relaxation, internal stress does not lead to cracking, and shearing strength by flexure and bending does not diminish with time. In order to measure loss in flexural strength, standard specimens (4 x 4 x 16 cm) are generally used for composite mortars.

Dimensional stability on the other hand is measured [10] by a dilatometer on 50 mm long specimens with cross section of 0,2 to 0,5 cm^2. The rate of temperature rise is 1°C/min. and expansion is recorded optically or electronically. A typical illustration is presented in Fig. 5. In the region of instability, T_i, temperature rise leads to contraction. In this temperature interval, the polymeric contraction of fibers prevails over thermal expansion. DEGEIMBRE [10] got very similar results when he measured the electrical resistance as a function of temperature. In proportion to the network formation, conduction is hindered, thus increasing resistance. In the region of instability, T_i, increasing temperature simultaneously produces thermal softening of the network which reduces strength and at the same time increases network cross linkage due to the application of activation energy, which produces increased strength. The resistivity measurement method is thus complimentary to that of thermal expansion for evaluating thermal instability of the network. This method demands a specialized apparatus because it concerns the measurement of variation of degree of insulation. Note that in the region of solidification, the binder's reactivity may be evaluated by variation in viscosity, increase of hardness, or even by variation of propagation speed of elastic ultrasonic frequency waves on the order of 0,5 MHz [13] .

2.5 Hydraulic Instability.

It has been stated that certain structures contain micro-pores susceptible to dilation, in the presence of water, due to capillary pressure. The result is that a small absorption of water leads to a greater variation in dimensions. This phenomenon, though little known in the field of polymerizable binders, merits close examination because it could be a cause for the reduction of adherence to the substrate comparable in magnitude to the contraction phenomenon. Preliminary observations made on this subject show that the dimensional growth can be very slow and take several months.

3. FILLERS.

Besides additives (catalysts, accelerators, hardeners, solvents, reactive solvents, softeners,etc...) included in a binder, pigments or fillers frequently are added. Fillers can be classified as organic or inorganic types. The first group contains vegetable organic fillers (wood particles), carbon black, or polymers (PVC particles). Inorganic fillers are of mineral, metallic or glass types. Concerning the form of the particles, we distinguish granular fillers, filiform fillers or fillers such as grains of sand, zinc oxide, glass fiber, metal threads, or lamillar slate. Industry has put at our disposal a great variety of fillers, in terms of their nature and the form of granules. It is therefore possible to find a filler that is the most appropriate for the composite chosen. The presence of fillers modifies the rheological, mechanical and physical characteristics of the binder : the temperature t_{50} increases, the temperature T_{max} is lowered, and the elastic modulus increases in proportion to filler content, and compressive strength increases as the shear strength diminishes. The volume effect for granule fillers is shown in Fig. 6. Filiform fillers can take the form of contained filaments. Thus, the composite acquires anistropic characteristics.

Dispersed fillers are distinguished by their nature, specific gravity, granular form, granular size curves, and specific surface. Determination of these characteristics is standardized by specifications designed for the formulation of paints and composite mortars. Evaluation of the adherence of these fillers to the binder remains to be standardized. Presently, the adhesives' effect is judged by the volume behavior of the composite.

4. COMPOSITES.

The nature and proportion of fillers and granular characteristics considerably affect the rheological, physical and mechanical characteristics of the composite. The triangle in Figure 6 represents the volume composition of a composite : $C + L + V = 1$ where C is the proportion of the volume of the filler, L is the volume proportion of the binder, and V is the proportion of voids. Thus, the coordinates of a point define the composition of the composite. At the right, $C = 1$, $L = 1$, is a plot of points which characterize the saturated structure without voids (2d). In this case, each granule is surrounded by a film of binder which fills the interstices between particles. Workability of the mass is determined by the ability of the composite to keep its cohesiveness during manufacture by remaining homogenous as well as remaining compact without voids by consuming a minimum of energy.
Workability diminishes as the binder's proportion is reduced and as the specific surface of the filler increases. In the theoretical research work to develop optimum formulations, workability of the composite must be considered as well as the results of rapid physical measurements under conditions comparable to those at the construction site.

The mechanical characteristics of the composites in a solid state are measured by the use of standard specimens (4 x 4 x 16 cm.) for strength, modulus of elasticity in bending and compression after 7 days of aging (one day solidification and stripping plus 6 days storage in a standard atmosphere ISO R-291). These same measurements should be repeated on specimens kept for 7 days at 80°C, then as a function of temperature as discussed in Section 2.2. The dimensional stability and impact resistance should be measured after the storage period on specimens 1 x 1,5 x 12 cm. in size. Impact resistance is a function of temperature, and it is useful to know this function for a given composite. The dimensions for the rounded aggregate rarely exceed 3 mm; thus,the specimen's shape cited above reflects correctly the characteristics of the composite to be examined. The filiform fillers considerably improve the shear and flexural strength of the composites, and are used for this purpose. Also one quite often encounters filiform fillers incorporated in a composite containing granular fillers.

5. PREFABRICATED ELEMENTS.

Application to prefabricated elements, particularly to the exterior, requires a complimentary study on the effect of shape on the reaction results as well as on that of durability in a long-term application. It is true in this case that observation of actual elements on site is most important. However, it is essential to devise accelerated methods for simulating the environment in order to correct the composition of shape of an object for its intended purpose. In this way, the author constructed at the Institute of Civil Engineering, a vertical test slab 3,5 x 2,5 m. in reinforced concrete (8 cm. thick) to be used as a support for a substrate during tests simulating exterior conditions. A study of the behaviour of exterior siding sheets (1,8 x 1 m., and 2 cm. thick) made of mortar with a resin [15] could utilize such a device.

The sheet is attached to a test slab by clamps. The exterior temperature of the sheet to be tested is controlled by infrared rays and follows, at first, a graph which is later extrapolated. Thus, the temperature reaches 80°C and is maintained at this level for an hour. The difference in temperature between the two faces increases toward the light source. The rod connects the non-heated side of the test sheet to an appartus measuring sag. If the sag is accompanied by a shortening of the horizontal axis of the sheet, clamp stresses develop whose value and distribution depends on the type of attachment and its rigidity. Post-polymerization produced by thermal energy causes a non-homogenous contraction in the transverse section of the sheet which at first reduces the value of the thermal sag on the graph but then, after cooling, produces a reversal. The solar cycle maintaining the surface radiated at 80°C is terminated by spraying with a water jet at about 10°C. Thus, the temperature of the heated surface of the sheet is suddenly brought to room temperature. This cycle is repeated after a rest period. The maximum distortions and those corresponding to the rest period are shown in Figure 8. It is stated that the effect of post-polymerization is particularly evident during the first cycle of solar radiation.

CONCLUSIONS.

Although the study of binder reactivity and characteristics of aggregates and composites are most important in designing the binder's composition and adapting it in the best manner to its proposed use, the dimensional stability test of an element in actual size and of its reaction to conditions which simulate actual environment is necessary. In fact, the deduction of reactions by superposition of preliminary reactions is illusory. Resin binders and composites containing them are characterized by a weak thermal conductivity coefficient. This brings about a great difference between surface temperatures and a large thermal gradient within an element.

When such a material is applied to another surface, concrete for example, the difference in deformation does not result from the difference of the thermal expansion coefficients of two materials alone, but from a great differential on the one hand, and eventual contraction on the other.

Knowledge of these facts facilitates development of composites formulated for specific purposes.

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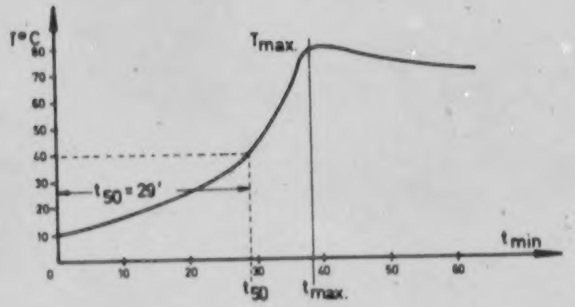


Fig. 1

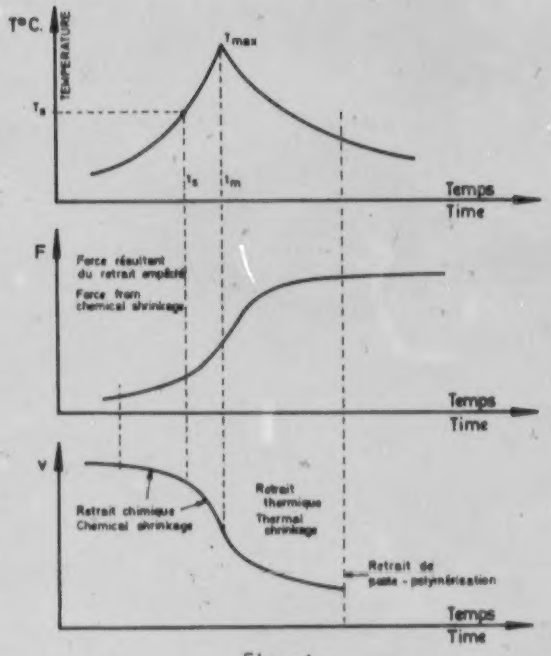
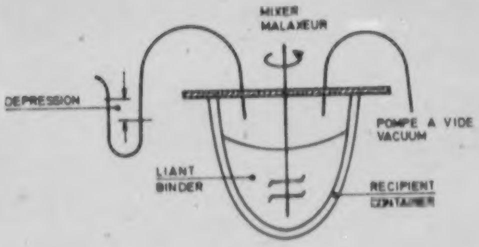


Fig. 4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MALAXEUR
DEPRESSION
POMPE A VIDE
VACUUM
LIANT
BINDER
RECIPIENT
CONTAINER

Fig. 2

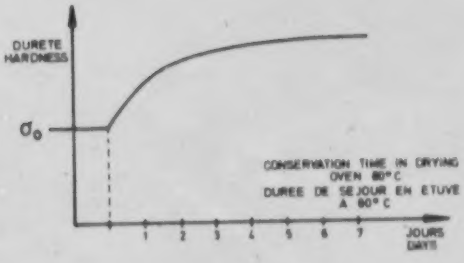


Fig. 3

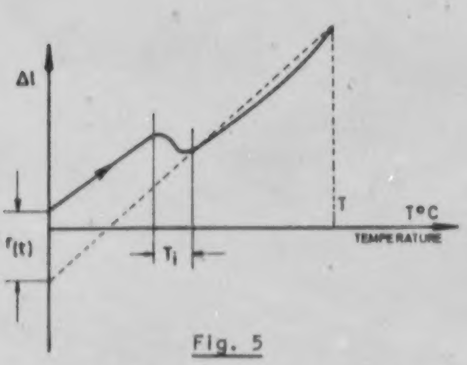
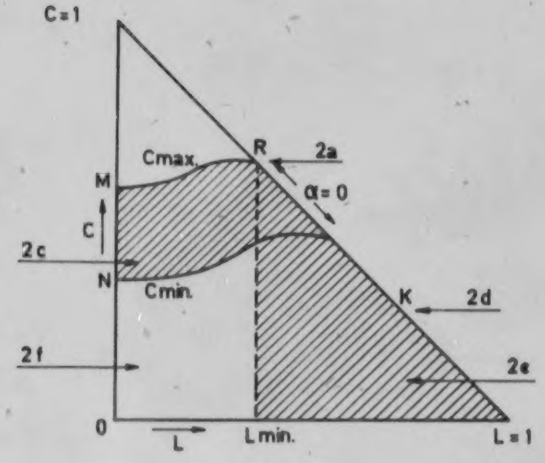


Fig. 5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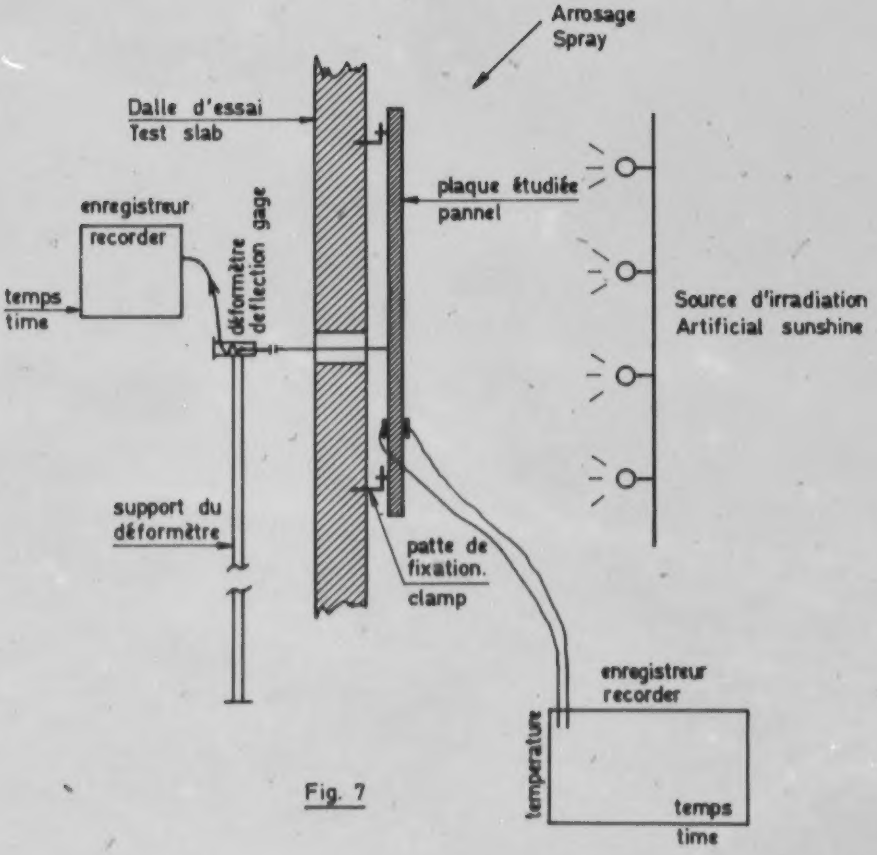
Cmax.
R
2a
α=0
M
C
2c
N
Cmin.
K
2d
2f
2e
0
L
Lmin.
L=1

Fig. 6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Spray
Dalle d'essai
Test slab
plaque étudiée
pannel
enregistreur
recorder
temps
time
déformètre
deflection gage
Source d'irradiation
Artificial sunshine
support du
déformètre
patte de
fixation.
clamp
enregistreur
recorder
temperature
temps
time

Fig. 7

DEFORMATION EN FONCTION DE LA TEMPERATURE DES 2 PAROIS AU COURS DES 10 CYCLES D'ENSOLEILLEMENT ARTIFICIEL.
DILATATION - TEMPERATURE MEASURED ON TWO SURFACES DURING 10 CYCLES SIMULATED SUNSHINE EXPOSURE.

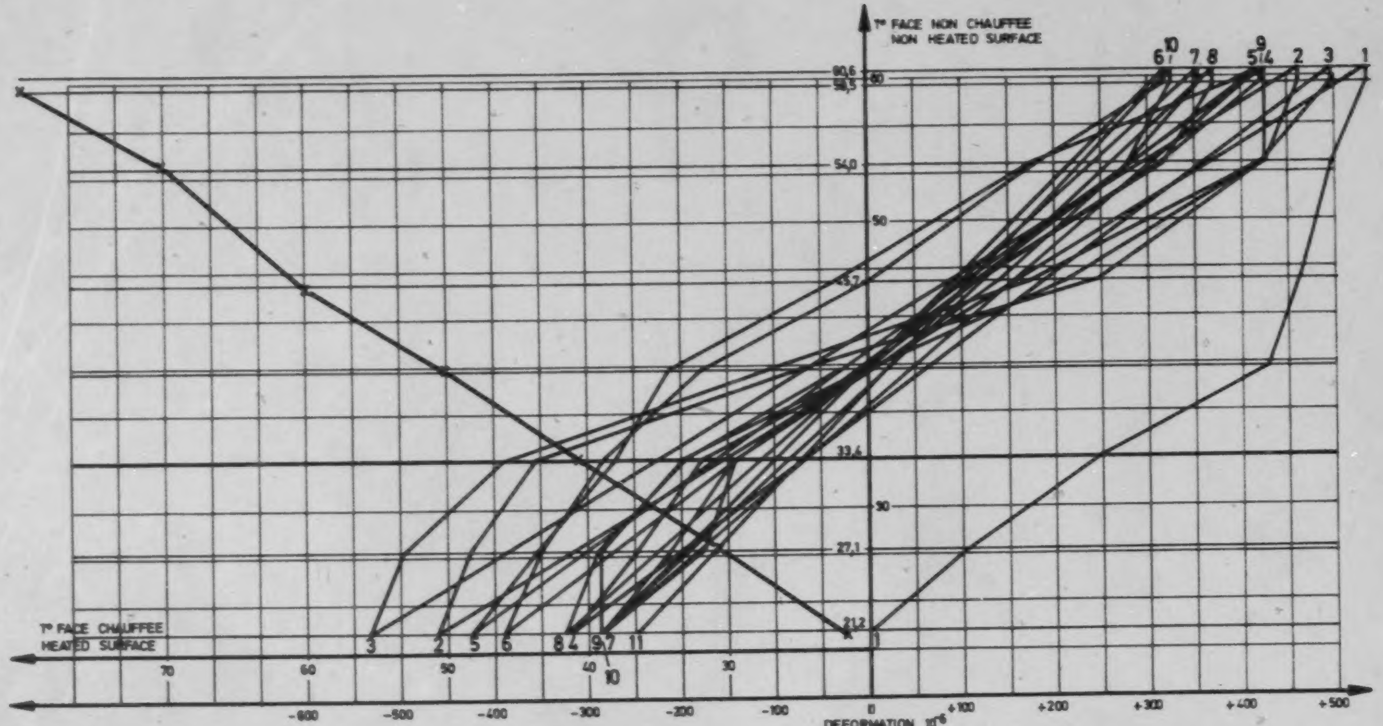

Fig. 8

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

Natural and Artificial Weathering Performance of Rigid Polyvinyl Chloride (PVC) and Other Plastic Materials

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Rigid polyvinyl chloride and other synthetic plastics as exterior building materials are relatively new, but their use, fabrication and distribution are well-documented. Weathering performance of these materials is taking time to evaluate because of the wide range of variables involved, the general inertness of the substances and the lack of knowledge of the proper test parameters to use. An artificial weathering test method has been developed which takes into account the vital role of moisture in the degradation of plastics. Dual consideration is given to the deleterious effects of ultra-violet radiation alone. Many of the results of this combined method of evaluation have correlated well on an accelerated basis with outdoor performance. The efficacy of outdoor weathering emphasizes the need for a closer examination of UV radiation sources and test atmospheres. Color and surface changes are followed during weathering, and measures of stability are expressed as color difference units and gloss variations. Color acceptability may be evaluated by means of color triangulation. Changes in impact resistance in rigid PVC are as important as the influence of atmospheric pollutants during the natural weathering process. Both phenomena require duplication artificially with the hope of determining time equivalence between the two media.

Si le chlorure de polyvinyl et d'autres plastiques synthétiques sont relativement nouveaux en tant que matériaux de construction extérieure, on est cependant bien informé de leur utilisation, fabrication et distribution. L'action des conditions atmosphériques sur ces matériaux est lente à évaluer à cause du grand nombre de variables impliquées, de l'inertie intrinsèque des substances et du manque de connaissance des paramètres d'essai appropriés. Une méthode d'épreuve sous conditions atmosphériques artificielles a été développée, elle tient compte du rôle primodial de l'humidité dans la détérioration des matières plastiques. Importance double a été accordée aux effets nocifs des seules radiations ultra-violettes. Nombre de résultats de cette méthode d'évaluation combinée se trouvent en bonne corrélation avec la performance extérieure sur une base accélérée. L'efficacité de l'exposition naturelle souligne le besoin d'un examen approfondi des sources de radiations ultra-violettes et des épreuves atmosphériques. Les changements de couleur et de surface sont suivis pendant l'exposition à l'atmosphère et les mesures de stabilité sont exprimées en différences de couleur et de variations de lustre. L'évaluation de la couleur peut se faire par le moyen du triangle des couleurs. Les changements de résistance au choc du P.V.C. rigide sont aussi importants que l'influence des polutions atmosphériques pendant l'exposition aux intempéries. Les deux phénomènes exigent une duplication artificielle dans l'espoir de déterminer une equivalence de temps entre les deux milieux.

Key words: Atmospheric pollutants; color - difference and representation; impact resistance; plastics; rigid polyvinyl chloride (PVC); test methods; ultra-violet (UV) radiation; water vapor; weathering - artificial and natural; yellowing.

1. Introduction

Rigid polyvinyl chloride (PVC) and other synthetic plastics as exterior building materials are relatively new, but their use, fabrication and distribution are well-documented (1)[1] (2). Weathering performance of these materials is requiring time to evaluate because of the wide range of variables involved, the general inertness of the substances and the lack of knowledge of the proper test parameters. The findings presented in this paper are based on pigmented compounds, unless otherwise specified.

In order to predict the natural weathering performance of rigid PVC and other plastic materials, there appeared a need for test procedures to reproduce rapidly and accurately on a synthetic basis the observable and unobservable changes taking place on the surface of and within the plastic compounds. A starting point was in the use of water vapor at elevated temperatures, in conjunction with ultra-violet radiation, to duplicate the greying or "whitening" of black, rigid PVC (3) (4).

An example of this phenomenon is illustrated by figure 1. The vapor cycle was performed as a separate step apart from the UV exposures and its effect is shown by the vertical segments of the EB and D curves as whitening took place. During both artificial and natural weathering, the initiation of whitening of black, rigid PVC was apparently due to the formation of micropores in the surface which in turn retained condensed water vapor, resulting in light scattering. Examination of the surfaces by replication techniques in conjunction with the transmission electron microscope and directly with the scanning electron microscope revealed the pore structures. Moderate heating of the PVC drove off the absorbed moisture, thereby eliminating light scattering and restoring its blackness. Dark-colored PVC compounds perform generally in the same fashion.

Through curves EB (Sarnia) and D (Sarnia) and EB (Bird) and D (Bird), figure 1 also shows differences in rates of whitening of black, rigid PVC depending on the location of outdoor exposure test sites. Lack of whitening outdoors in excess of 3 years, however, was shown by a black acrylic laminate. Curve C indicated that a black, rigid PVC compound could withstand UV-vapor cycling without appreciable whitening, but it could not be satisfactorily extruded.

The same UV-vapor cycling was found to account for the continual white appearance outdoors of some white, rigid PVC products as compared with appreciable yellowing attributable to UV radiation alone. In some cases, tan lines developed during both natural and artificial exposures; the lines disappeared in a short time by addition of vapor cycling to the artificial UV exposure and eventually did so outdoors on vertical sidewalls with prolonged exposures in excess of a year (3).

While exposures to UV radiation and UV-vapor cycling produced fairly rapid results, one particular experiment pointed up a need for appreciation of the efficacy of natural ultraviolet, visible, and infra-red radiation in combination with moisture. The Yellowness Index of an extensively yellowed sample of white, rigid PVC decreased about 5 points in 16 hours, as shown by curve 10 of figure 3; it had been placed on a 45° test deck facing SSW at about 3:30 p.m. on the previous afternoon in September. Similar changes in the laboratory require the use of elevated temperatures, such as indicated by curve 9 of figure 3.

In the case of extruded white, rigid PVC, the scanning electron microscope showed surface chalking resulting from outdoor exposure and appreciable surface porosity.

Thus we became involved with several factors affecting the weathering performance of rigid PVC and other plastic materials and came to realise the need for measuring such performance on the finished product.

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[1] Figures in parentheses indicate the literature references at the end of this paper.

2. Performance Comparisons

The many early "weathering" comparisons of rigid PVC compounds at Bird & Son, inc., have provided a basis for the recognition of differences between plastic materials, leading toward further selective evaluations. An example is the following of changes in yellowness of a white, rigid PVC compound E during numerous types of exposures, such as laboratory UV radiation (fluorescent sun lamp/black lamp and carbon and xenon arcs) and outdoors, under both wet and dry conditions. This compound has been found to yellow in the FSL/BL, carbon, and xenon arc units and outdoors when shielded from moisture, but does not yellow appreciably outdoors when exposed to moisture - rain, snow, dew and so forth. Its FSL/BL UV curve is shown as 1 and its whitening curve as 10 in figure 3.

From the standpoint of general performance, it would appear that a white compound M which does not yellow as extensively as compound E under FSL/BL UV radiation, yet remains white when exposed to water vapor - curves 8 and 9 of figure 3, might be considered less vulnerable or an improved building material, an objective we continually seek. Mechanical properties must also be evaluated, however, on a comparative basis.

It was found that not all of the phenomena produced outdoors were being duplicated by artificial weathering methods. One example has been the vapor cycling of pastel yellow and green, rigid PVC whereby color differences have been slightly lower than those experienced outdoors. As is evident in trying to equate performance between the two methods, it is not fully known at this time all of the discrepancies which exist.

Exploration into possible differences in reaction of various plastics to different sources of UV radiation (3) has produced interesting insights. A particular white, rigid PVC compound J became quite yellow when exposed to FSL/BL UV radiation (curve 5 of figure 3), but remained white when exposed 1000 hours to a xenon arc while sealed in a Vycor tube and also outdoors while shielded only from the cleansing action of moisture (curve 7 of figure 3). When exposed directly to the xenon arc in an Atlas Weather-Ometer Model 600 WR at 40% relative humidity for 95 days it yellowed somewhat as seen by curve 6 of figure 3.

A second marked difference in results between sources of UV was obtained with three white polycarbonates exposed to FSL/BL, xenon arc, and outdoor radiation; results are shown in figure 2. The samples exposed to the FSL/BL yellowed considerably in one week and did not clarify with vapor cycling. This persistence of intense yellow discoloration during the vapor cycle was viewed as an ideal approach to obtaining equivalence values between artificial and outdoor weathering under the prevailing conditions. One polycarbonate sample on the test deck yellowed appreciably in two months, while the other two remained essentially white during six months of exposure. The rates of yellowing upon direct exposure to the xenon arc were closer to those of the FSL/BL than outdoors, but a certain resolution occurred as was effected outdoors, whereas little or no resolution of differences between the three polycarbonate samples was obtained through exposure to the FSL/BL UV. Thus, no equivalence values were obtained. It should be mentioned here that the Yellowness Index values for the samples exposed to the xenon arc were calculated according to ASTM D 1925-70 equation

$$\text{Y.I.} = \frac{100(1.28X_{\text{CIE}} - 1.06X_{\text{CIE}})}{Y_{\text{CIE}}} \qquad (1)$$

while

$$\text{Y.I.} = \frac{100\ (A-B)}{G} \qquad (2)$$

was used for the remaining white samples. The latter equation, also found in ASTM D 1925-70, is used similarly by British Titan Products to calculate "Colour Index" for whites (5).

An anomalous result has been obtained with compound E while sealed with NO_2 in a Vycor tube during exposure to the xenon arc. The gas became colorless in about 40-50 hours' time, and at the end of only 168 hours of exposure the white, rigid PVC strip was dark beige along the edges and at the ends but almost black along the center. This rapid, dark discoloration did not occur in over 500 hours of exposure in the FSL/BL nor in almost 700 hours of outdoor exposure. This area requires further investigation.

3. Atmospheric Gases

As an initial examination of the possible affect of atmospheric gases on rigid PVC while exposed to ultra-violet radiation (3), eleven Vycor test tubes, containing strips of white, rigid PVC approximately 3/4" x 7-1/4" in size, were installed on a 45° test deck facing SSW, eight of the tubes being separately filled with ammonia, carbon monoxide, hydrogen sulfide, methane, nitrous oxide, nitric oxide, nitrogen dioxide or sulfur dioxide. Since the gas tubes were sealed with neoprene stoppers, a control sample (compound E) was also sealed in a tube with only an air atmosphere. Along with these tubes were two more with open ends, one containing a control strip and the other a strip of compound J which was known to yellow extensively in FSL/BL UV radiation; see curve 5 of figure 3.

Cloudy weather prevailed for several days at the start of the exposure period in mid-April 1971, but in 22 hours, the sample in SO_2 had begun to darken and by 144 hours the strip was almost black, and the inside wall of the tube was hazy; the reverse side of the strip facing the deck was uniform, but slightly yellowed. A similar test using SO_2, but exposing strips of different white, rigid PVC compounds in the FSL/BL unit, produced similar results, differing only in the type of discoloration of the PVC. The primary reactions appeared to be those of reduction of the SO_2 to elemental sulfur, recombination of the stabilizers' heavy metal to form colored sulfides, such as tin, barium, and cadmium, and some oxidation of the PVC.

Although the concentrations of gases used in these experiments were excessive and hardly as low as air-pollution levels, the reactions involved may account for colored areas in the proximity of particulate matter deposited on white PVC siding as observed in an industrial area. The particle might become a "carrier" of a relatively high concentration of reactants to the surface of the PVC, resulting in discoloration with continued exposure.

The sample enclosed in NO_2 showed a different phenomenon, wherein initial discoloration of the strip could not be detected visually because of the color of the gas, but after 29 days the strip was seen to be yellowish-tan and the gas colorless. When the tube was opened, the brown color of NO_2 immediately reappeared, indicating a redox reaction whereby the PVC reacted with the oxygen provided by the reduction of NO_2 to NO. The Yellowness Index of the white strip had increased from 1.1 to about 17.3 and 26 days later, while the strip was stored in the dark, it has increased to 79.1.

Similar results again were produced with the FSL/BL unit, exposing different rigid PVC compounds in NO_2, with differences in discoloration again depending on the particular compound. In this case, however, the increase in Yellowness Index of compound E after standing in the dark for 27 days amounted to only about 4.8 points, possibly indicative of the differences in UV radiation.

The sample enclosed in NH_3 increased in Yellowness Index from 1.1 to 7.7 in 33 days, while changing in the green tristimulus value only from about 75.0 to 73.6, whereas in 63 days of exposure the sample enclosed in H_2S increased only about 0.1 point in Yellowness Index, but the green tristimulus value decreased from about 75.2 to 63.8, indicating general darkening or greying.

During the same 63-day period, the control strip in the closed-end tube on the test deck showed a slight decrease in yellowness whereas the sample in the open-end tube showed an increase. After 88 days, the additional 25 days being in June and July, the open-end control increased about 6.2 points, the closed-end control about 1.9 points and the open-end compound J about 2.0 points in Yellowness Index. At 123 days, as can be seen by curves 3, 4 and 7 of figure 3, compound J had still changed very little in Y.I. while the compound E strips were continuing to increase in yellowness, the one in the open-end tube at the higher rate presumably because of the continual supply of oxygen.

Of the compound E strips, the specimen in the N_2O-containing tube, which had remained sealed for 123 days of exposure, showed the least change in Yellowness Index, increasing by about 5.5 points (X in figure 3).

It would thus appear that closed Vycor test tubes have restricted use for testing such as rigid PVC and other plastic materials which are intended for continuous outdoor exposure. The above findings have proven valuable, but their interpretation and extension must be carefully considered when relating them to performance under natural weathering.

No work along these lines has as yet been done with mixtures of gases.

4. Polymeric Changes

With further reference to the xenon arc and its affect on rigid PVC, it has been noted that even though the rate of yellow discoloration for white compound E was lower than with the FSL/BL, the rate of surface degradation appeared about the same in both units. Indication that degradation of the polymer was taking place as a result of UV exposure was obtained by folding a 3/8" x 2-1/8" strip of the sample 180° on itself such that the exposed surface was in tension. Unexposed stock showed no cracking as a result of such folding, but micro-cracks appeared along the fold after about 250 hours of the radiation and at 1000 hours the cracks were more extensive, but of about equal size and number in each sample.

This test provides a rapid, qualitative evaluation of changes in impact resistance during artificial and natural weathering. It revealed the differences in degradation between samples of rigid PVC exposed to only UV radiation versus those exposed to UV-vapor cycling. The former tended to show deeper and more extensive cracking than the latter which were apparently somewhat plasticized by the moisture as reported on for outdoor weathering by Reinisch and Gloria (6). Yellowing, however, has not always been accompanied by the degradation which causes cracking on folding or results in appreciable decrease in impact resistance.

The deeper type of cracking in rigid PVC, as produced in some cases by FSL/BL UV radiation, was duplicated outdoors by the strip of white, rigid PVC enclosed with NO_2 gas in the Vycor test tube, exposed to natural UV radiation for 29 days, removed from the tube and stored in the dark for over 26 days. The strip cracked about 90% through its thickness when folded 180° on itself, indicating polymeric degradation, probably in depth, resulting from oxidation (7). Similar strips artifically exposed with NO_2 also cracked. Where some rigid PVC compounds crack in depth to various degrees when folded after weathering, some acrylic films decrease in elasticity and become brittle, the phenomena occurring during both natural and artificial weathering exposures. Acrylics, however, exhibit generally greater color stability (3) (4) and have been used as laminates over such rigid substrates as ABS and PVC.

5. Color Difference

During the weathering of plastics used as building materials, it is highly desirable to maintain a record of color stability, expressed as a measure of resistance to change. One method of following the performance of a product is to make periodic color measurements and show any observed change as color difference. This value represents only a degree of magnitude; it lacks direction. It also appears to depend upon the particular instrument employed for measurement and/or the particular method used for making calculations with the tristimulus values obtained.

In a recent comparison of color difference values calculated for essentially the same paired samples, employing five different instruments in as many different laboratories and by as many different personnel, there appeared some general agreement for certain color pairs, but enough difference existed between other samples to raise question about any attempt at specifying units of color difference (8). The original color difference (E) values, as shown in Table 1. were calculated by means of Color Scale System C (ASTM D 2244-68) for the Photovolt 670, Scale A_2 for the Colormaster V, and Scale B_2 for the Hunter

D25A; the Reilly-Glasser Cube Root (8) was used for the Color-Eye D1 and method FMC II (Friele-MacAdam-Chickering) (9) for the G.E. Spectrophotometer. All other (E) values for the different instruments were calculated from their respective measured or converted values of green, amber, and blue or C.I.E. values. A similar examination of color difference in the paint industry in England produced comparable results (10).

Thus it would appear that all factors involved in a color measurement and color difference computation require enumeration (11). If the Judd transformation is employed, then the values would be in NBS units (12), all others being expressed as color difference (E) per the instrument and method of calculation used. This procedure would increase confidence in relating performance characteristics of plastic materials during weathering, artificial or natural, on a comparative basis and better relate color differences obtained at different locations through greater familiarity with the various color scale systems.

The question still remains as to how best to look at color and color changes resulting from weathering. A quick method of evaluating a color change is by tristimulus color triangulation as shown in figures 5 through 7. Figure 4 illustrates the basic triangles from 0% reflectance black to 100% reflectance white (4). They are used by drawing lines parallel to the respective bases and at the reflectance levels of the green, amber and blue values to form color triangles. Without further calculation the method shows, between any two triangles, the changes in lightness (ΔL) and in yellowness (Δ Y.I.) and provides an estimation of Δa and Δb. Being qualitative, however, the method lacks the quantitative values of the color difference (E), but when the two are used in combination, they provide a good "picture" of a color and its changes with weathering.

6. Conclusions

The several approaches to weathering constitute examination of the parts separately, such as ultra-violet radiation (FSL/BL, carbon and xenon arcs, outdoors), moisture (water spray, water vapor, outdoor humidity), temperature (low, moderate, elevated) and cycling (vapor at 80 hours or 168 hours, dark periods, continuous exposure vs. night and day) and then recombining them into the most appropriate form of artificial test procedure in the evaluation of anticipated performance.

The various approaches used thus far indicate that rigid PVC compounds are subject to such modification as to effect appreciable differences in performance during "weathering." The ultimate, of course, would be a compound which showed no change from its initial and preferred characteristics.

7. Acknowledgments

Credit goes to W. M. Stark and his associates at Esso Chemical Canada, Sarnia, Ontario for their co-operation in performing the xenon arc Weather-Ometer exposures, providing data relating to the outdoor weathering of certain black, rigid PVC compounds in the Sarnia area, and participating in the examination of color difference measurements. Thanks are also extended to those other firms who contributed data for the color difference evaluations.

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TABLE I.

COMPARATIVE EXAMINATION OF COLORS
Color Difference (E) Values

Instrument & Calculation Method

Color Pairs	Sample	Photovolt 670 Scale C	Photovolt 670 Cube Root A.C.B	Photovolt 670 Cube Root X.Y.Z	Photovolt 670 NBS Units	Colormaster V Scale C	Colormaster V Scale A2	Colormaster V Cube Root	Colormaster V NBS Units	Hunter D25A Scale C	Hunter D25A Scale B2	Hunter D25A Cube Root	Hunter D25A NBS Units	Color-Eye, D1 Scale C	Color-Eye, D1 Cube Root A.C.B	Color-Eye, D1 Cube Root X.Y.Z	Color-Eye, D1 NBS Units	G.E. Spectrophotometer Scale C	G.E. Spectrophotometer FMC II	G.E. Spectrophotometer Cube Root	G.E. Spectrophotometer NBS Units
Blacks	1.	9.9*	17.4	17.0	11.4	8.5	1° 7	12.7	4.6	-	-	-	-	8.1	12.2	12.2	4.3	-	-	-	-
	2.	9.8	16.4	16.3	10.8	-		-	-	8.5	8.5	12.9	4.5	-	-	-	-	-	-	-	-
	3.	13.8	20.5	20.4	10.6	-	-	-	-	-	-	-	-	-	-	-	-	-	17.0	6.8	4.3
White vs. Tan	1.	22.9	22.3	20.7	25.2	20.7	17.6	18.5	22.3	-	-	-	-	18.4	17.9	17.9	21.6	-	-	-	-
	2.	21.0	20.3	18.9	19.8	-	-	-	-	19.2	16.1	17.0	20.6	-	-	-	-	-	-	-	-
	3.	21.3	21.1	19.5	11.7	-	-	-	-	-	-	-	-	-	-	-	-	-	36.5	18.7	22.2
Tans	1.	3.7	3.3	3.3	3.6	3.1	3.2	2.9	2.9	-	-	-	-	3.0	3.0	3.0	2.9	-	-	-	-
	2.	3.9	4.0	3.8	4.1	-	-	-	-	3.8	2.9	3.8	3.7	-	-	-	-	-	-	-	-
	3.	6.0	6.4	6.0	6.7	-	-	-	-	-	-	-	-	-	-	-	-	-	13.0	6.0	6.6
Beiges	1.	13.8	12.3	12.2	14.4	13.6	12.0	11.9	20.4	-	-	-	-	13.4	11.8	11.8	13.9	-	-	-	-
	2.	14.4	12.7	12.6	14.8	-	-	-	-	14.3	14.2	12.4	14.3	-	-	-	-	-	-	-	-
	3.	14.6	12.8	12.7	14.8	-	-	-	-	-	-	-	-	-	-	-	-	-	27.0	11.9	13.7
Greens	1.	3.8	4.5	4.5	5.5	3.6	4.0	4.1	3.7	3.7	3.5	4.2	3.2	4.1	4.9	4.9	2.2	-	-	-	-
	2.	4.2	4.6	4.6	4.6	-	-	-	-	-	-	-	-	-	-	-	-	-	6.1	3.7	2.5
	3.	33.3	54.2	46.4	63.5	29.1	31.0	36.6	48.2	28.1	21.3	35.2	46.0	25.1	35.4	35.3	46.1	-	-	-	-
	4.	33.2	54.2	46.5	63.6	-	-	-	-	-	-	-	-	-	-	-	-	-	41.0	23.8	28.5
Yellows	1.	1.5	1.6	1.5	3.2	-	-	-	-	1.6	1.2	1.6	1.7	-	-	-	-	-	-	-	-
	2.	1.6	1.7	1.6	1.7	-	-	-	-	-	-	-	-	-	-	-	-	-	3.4	1.8	1.8

* Original data provided to two decimal places has been rounded to one.

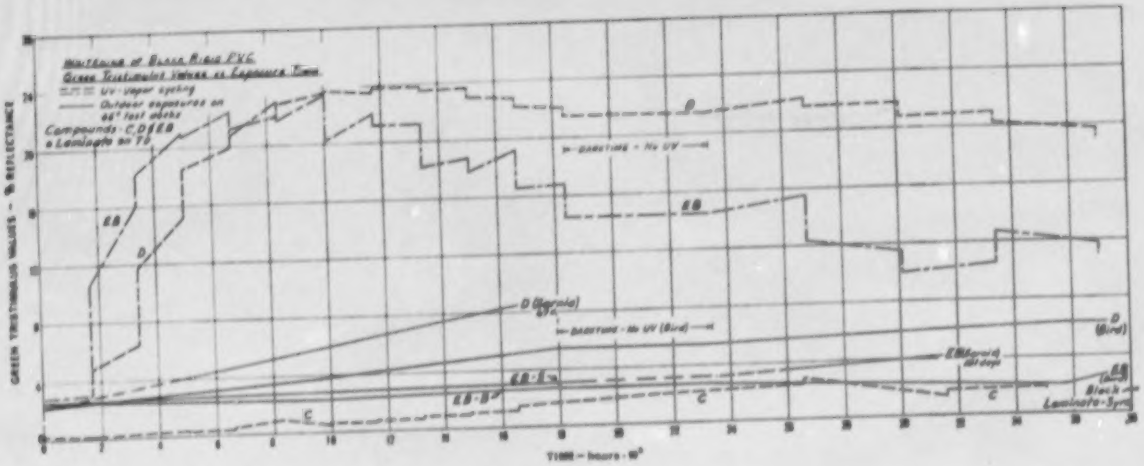


FIGURE 1

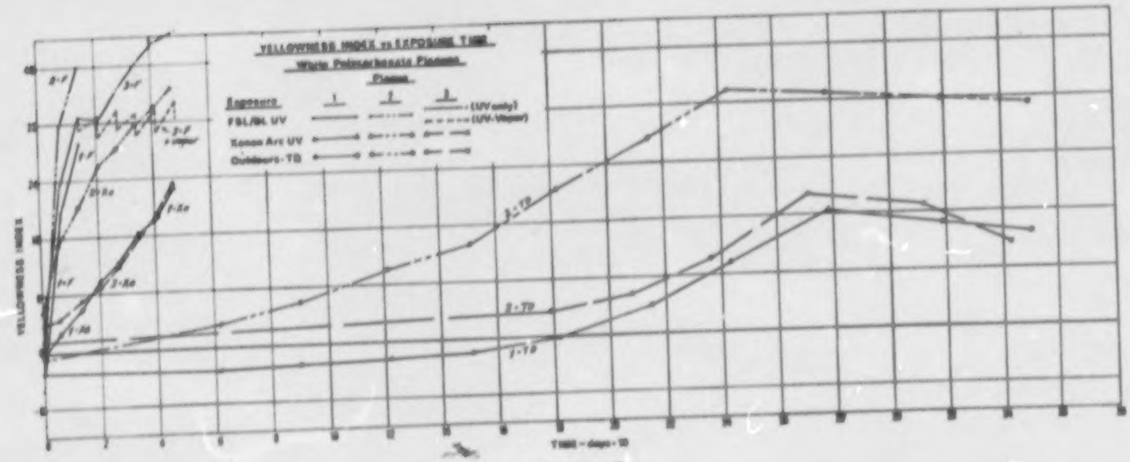


FIGURE 2

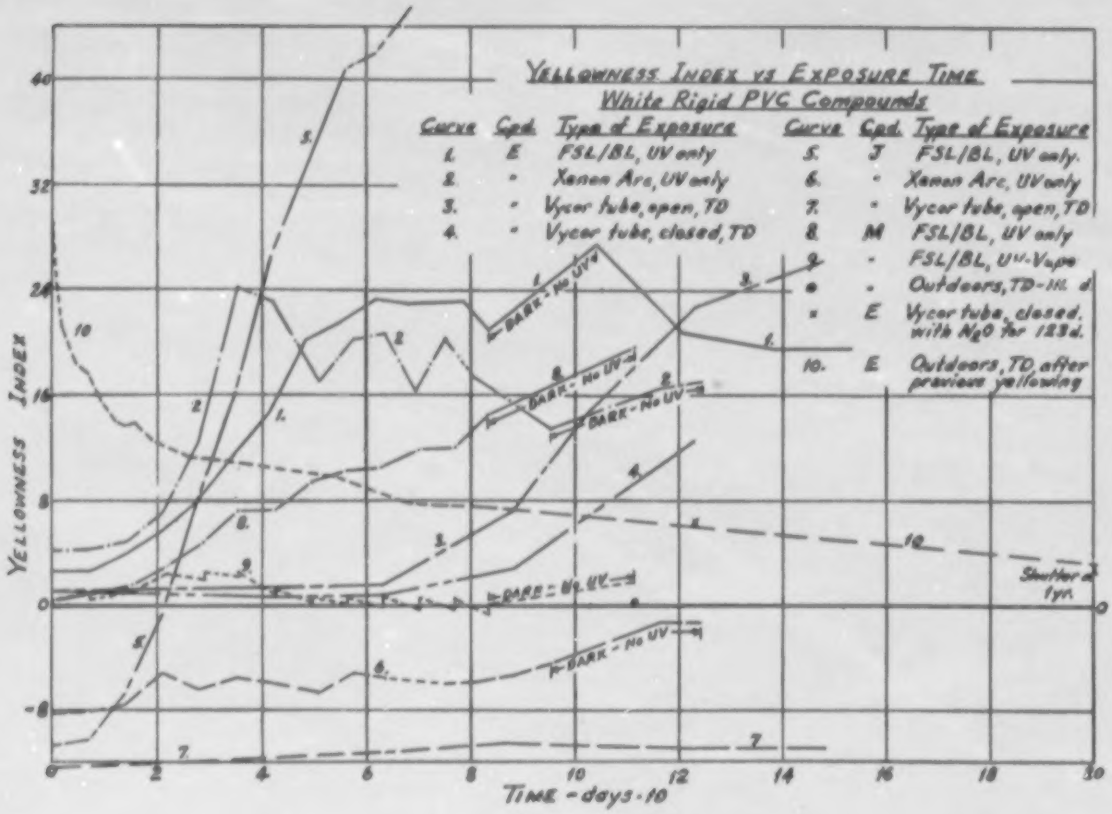

YELLOWNESS INDEX vs EXPOSURE TIME
White Rigid PVC Compounds
Curve Cpd. Type of Exposure
1. E FSL/BL, UV only
2. " Xenon Arc, UV only
3. " Vycor tube, open, TD
4. " Vycor tube, closed, TD
Curve Cpd. Type of Exposure
5. J FSL/BL, UV only.
6. " Xenon Arc, UV only
7. " Vycor tube, open, TD
8. M FSL/BL, UV only
9. " FSL/BL, UV-Vapor
● " Outdoors, TD-111 d
× E Vycor tube, closed, with N₂O for 123d.
10. E Outdoors, TD after previous yellowing
DARK - No UV
YELLOWNESS INDEX
TIME - days · 10
40
32
24
16
8
0
-8
0
2
4
6
8
10
12
14
16
18
20

FIGURE 3

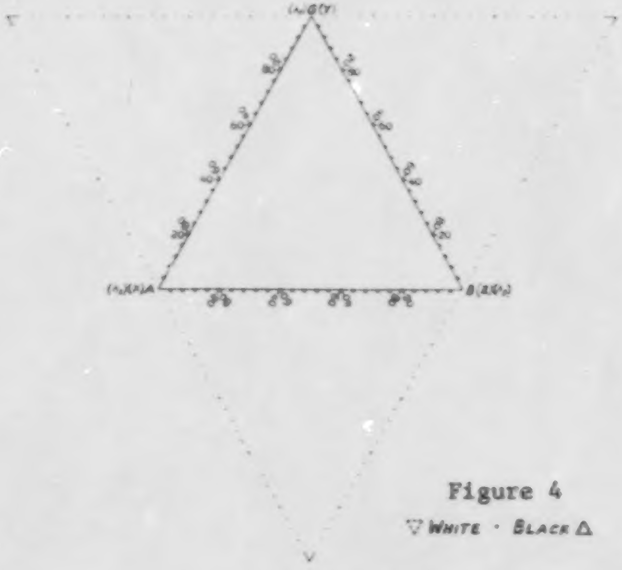
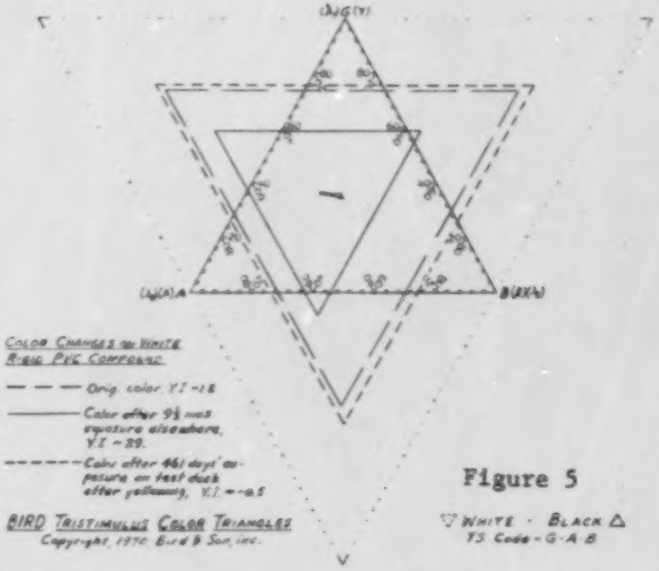


Figure 4

▽ WHITE · BLACK △



COLOR CHANGES ON WHITE RIGID PVC COMPOUND

- Orig. color. Y.I. -18
- Color after 9½ mos exposure elsewhere, Y.I. -29.
- Color after 461 days' exposure on test deck after yellowing, Y.I. = -0.5

BIRD TRISTIMULUS COLOR TRIANGLES
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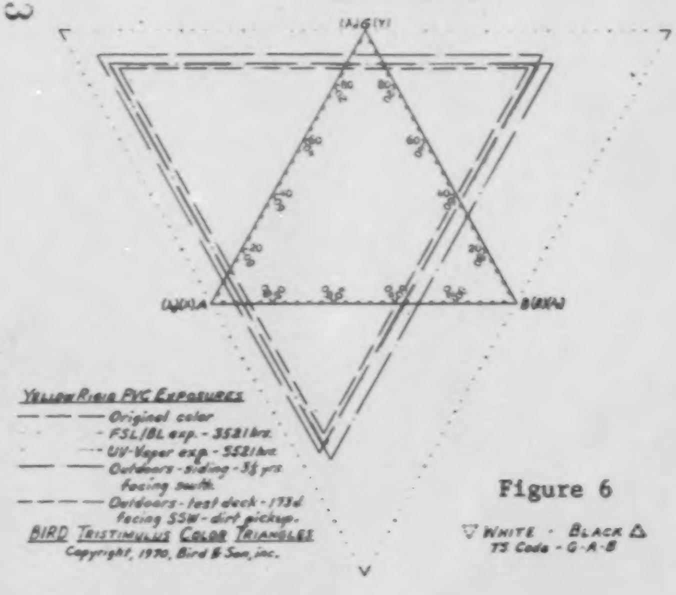
Figure 5

▽ WHITE · BLACK △
TS Code - G·A·B



YELLOW RIGID PVC EXPOSURES

- Original color
- FSL/BL exp. - 3521 hrs.
- UV-Vapor exp. - 5521 hrs.
- Outdoors - siding - 3½ yrs. facing south.
- Outdoors - test deck - 173d facing SSW - dirt pickup.

BIRD TRISTIMULUS COLOR TRIANGLES
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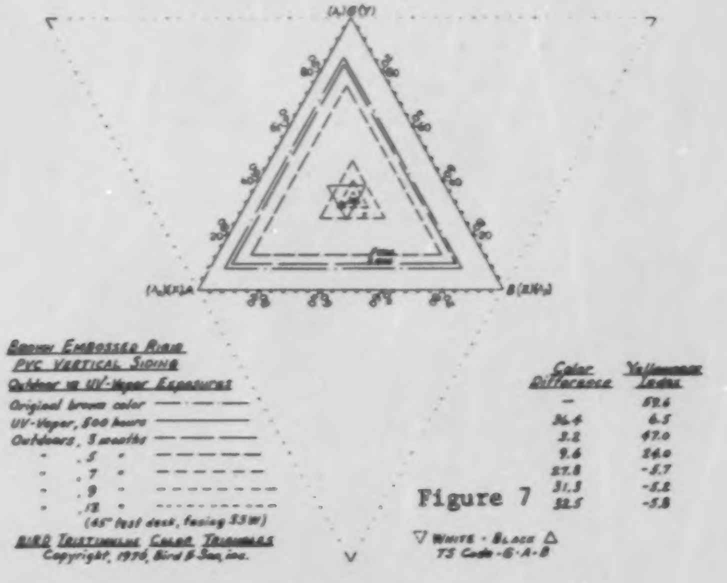
Figure 6

▽ WHITE · BLACK △
TS Code - G·A·B



BROWN EMBOSSED RIGID PVC VERTICAL SIDING
Outdoor vs UV-Vapor Exposures

- Original brown color
- UV-Vapor, 500 hours
- Outdoors, 3 months
- " , 5 "
- " , 7 "
- " , 9 "
- " , 12 "

(45° test deck, facing SSW)

BIRD TRISTIMULUS COLOR TRIANGLES
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Color Difference	Yellowness Index
—	59.6
36.4	6.5
3.2	47.0
9.6	24.0
27.8	-5.7
31.3	-5.2
32.5	-5.8

Figure 7

▽ WHITE · BLACK △
TS Code - G·A·B

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

Evaluation of Structural Adhesives for Use in Housing Systems

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As a result of the structural evaluation procedures developed for the "Operation BREAKTHROUGH" program, critical factors occurring in adhesive bonded structural assemblies were identified. The effects of aging, sustained-loading and adverse environmental conditions on these bonded areas were evaluated using small test specimens.

Typical results from this evaluation on two BREAKTHROUGH systems are presented. The results indicate that the accelerated aging procedure used here has a deteriorative effect on the strength of these systems. However, the magnitude of this effect was not judged to be great enough to reduce the strength of the final design below that required by the application. The results presented also show that the effects of adhesive thickness, temperature and sustained loading can be very significant and must be fully considered in design and structural evaluation.

Key words: Accelerated aging; adhesives; bonded structures; durability; glass fiber reinforced plastics; housing systems; Operation Breakthrough; paper honeycomb; performance criteria; structural sandwich.

La méthode d'évaluation de la construction utilisée pour le programme de l'"Opération BREAKTHROUGH" a permis d'identifier les zones critiques des surfaces assemblées par collage. Les effets de l'âge, de la charge continue et de conditions contraires du milieu sur ces surfaces collées ont été évalués à l'aide de petites éprouvettes d'essai.

On présente les résultats typiques de cette évaluation sur 2 systèmes BREAKTHROUGH. Les résultats indiquent qu'avec la colle appropriée, le vieillissement accéléré dans des conditions variables d'humidité et de température n'altère pas nécessairement l'adhérence plus que le degré requis par l'application. Les résultats présentés montrent aussi que les effets de l'épaisseur de colle, de la température et de la charge continue peuvent être trés significatifs et qu'ils doivent être pleinement pris en considération dans l'évaluation du projet et de la construction.

1. Introduction

One phase of the "Operation BREAKTHROUGH" [1][1] program by the Department of Housing and Urban Development is an evaluation of the structural adequacy of each proposed housing system. Two basic questions regarding structural performance must always be considered when evaluating each system. First, will the structure withstand service loads, i.e., is it safe; and second, will the structure perform well in service?

Because of the nature of the program many structural designs and details, which are unconventional with respect to housing, were expected and proposed. One type of unconventional detail which required test data was the proposed use of structural adhesive bonding in lieu of, or in addition to, conventional fastening devices. Adhesive bonding was proposed for use in a variety of applications and the proposed adhesives varied from the familar casein and reclaimed-rubber types to one which was not as yet commercially available.

The Building Research Division of the National Bureau of Standards (NBS), in its role as evaluator, had to determine the answer to the two basic questions for these adhesive applications.

Performance criteria were developed and used as a guide for evaluation of the proposed adhesive applications.

2. Scope

During the evaluation of the BREAKTHROUGH housing systems, it became evident that the construction industry had discovered the advantages of using structural adhesives in both replacing and reinforcing conventional fasteners. Unfortunately, some of the industry did not simultaneously discover the disadvantages and pitfalls that occur as a result of improper selection and use of adhesives. The reason for this lack of knowledge is due to inexperience, unfamiliarity with the products, and the lack of pertinent information from the adhesives industry on applications peculiar to the construction industry.

The adhesives industry consists of a few major manufacturers and hundreds of small formulators who produce thousands of adhesives. In general, these adhesives are sold without guarantees as to their performance. Most of the adhesives industry include statements in their literature which places the responsibility for the performance of the adhesives on the user.

Although warranties do not protect the consumer, most manufacturers do provide information regarding the proper method of use and the resultant performance that may be expected of their adhesives. One problem is that the available information on a specific adhesive does not always indicate whether it should be used in a particular application. This frequently is due to the fact that the manufacturer or formulator has never been approached by a potential, volume consumer for information regarding the use of an adhesive for a specific, innovative application.

For example, in the use of the solvent-based, mastic adhesives the available data may describe the strength of a wood-to-wood bond after various aging periods under various environmental conditions; however, they may not describe the strength of wood-to-metal or metal-to-metal bonds which are sometimes required by the user. The strength of this type of adhesive, and of the bond, is a function of the loss of the solvent from the adhesive through evaporation. Thus, it is evident that the strength gain with time depends on factors such as the types of materials bonded, thickness of adhesive and environmental conditions. The effect of most of these factors can be determined rather easily using conventional short term test such as tensile or shear strength. The major problem in evaluating structural adhesives is the determination of the long term effects of environmental factors, i.e., durability.

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[1] Numbers in brackets refer to references listed at the end of this report.

One must be primarily concerned with both the durability of the adhesive bond, and the adhesive. For a durable bond, the adhesive and the adherends must be physically and chemically compatible with each other and this compatibility must not change significantly with age and environmental conditions.

Within limits, the strength of a cured adhesive and its adjunct adhesive bond generally decreases with an increase in temperature and the adhesive itself can degrade with age. Furthermore, the strength of the bond will be influenced by the rate of loading; and its strength under sustained-load will be less than its short-term strength. For example, in the case of thermoplastic adhesives, the deleterious effects of elevated temperatures, often combined with poor resistance to creep is frequently much greater than in the case of thermoset, or vulcanized, adhesives.

All the above mentioned factors must be evaluated for each adhesive and each application. This is especially important for adhesive applications where the bond strength is a determinate factor in the safety of the product.

To minimize the testing required for "Operation BREAKTHROUGH", structural adhesive applications were classified as follows:

Class A - Structural uses where the adhesive bond is required to maintain both the load-carrying capacity (safety) and the load-deflection characteristics of the structural system (serviceability).

Class B - Structural uses where the bond is required to maintain only the deflection characteristics of the system and where failure of the bond will not significantly reduce the load-carrying capacity.

Class C - Structural uses where the bond is required for a short period during manufacturing, transportation or erection procedures.

There are many standard methods [2], [3] which can be used to test the properties of adhesives and adhesive bonds under various environmental conditions. Some accelerated aging methods have also been standardized. However, there are no standard procedures for determining the suitability of an adhesive for specific applications in housing.

The suitability of the adhesives employed in some of the "Operation BREAKTHROUGH" systems is being determined on a case-to-case basis after consideration of test data from the adhesive manufacturer, the housing system producer and NBS. In general, standard test methods are used although variations or modifications are sometimes required in the evaluation of adhesives for certain applications.

Minimum test performance requirements are determined after a structural evaluation of the system establishes the required contribution of the adhesive bond to structural integrity.

3. Structural Evaluation

Of the 22 housing systems in the BREAKTHROUGH program 14 are using adhesives in structural applications. Of these 14 systems, 9 can be considered to be more or less conventional low-rise construction except for the extensive use of adhesives. Figure 1 illustrates typical uses for adhesives in the 9 conventionally framed systems. In systems where reduced nailing is used in conjunction with an adhesive in floors, roofs and walls the use is classified as a Class B application.

Three of the 14 systems utilize structural sandwich panels having more or less continuous cores and two have proposed the use of adhesive bonded stressed-skin panels. When adhesives are used in the sandwich or the stressed-skin panel systems the use is classified as a Class A application. As an example of the evaluation required for such applications some of the testing performed for two sandwich panel systems, identified as Systems No. 1 and No. 2, are described below.

3.1 System No. 1

System No. 1 housing units consist of 3 in. (7.6 cm) thick panels used in the roof, walls, and floors. The wall and floor panels are attached to a steel grade beam foundation system as shown in Figure 2. These panels consist of a resin impregnated, paper honeycomb core with a steel sheet bonded to each side with an adhesive. Urethane foam is pressed into the honeycomb prior to final assembly to improve thermal properties. Wood edge members are fastened to all edges of the panels.

The exterior surfaces of the roof panels on the completed housing units are intended to be exposed to the weather, with no additional roofing material applied, other than flashing and sealants at the panel joints and at the intersections with the wall panels. The flexural behavior of the roof panels after exposure to various laboratory conditioning procedures was evaluated to determine the effect of various environmental conditions on the structural performance of the panel. The manufacturer indicates that these roof panels are designed for a snow load of 30 psf (146 kgf/sq. m.)[2].

Three full-size prototype roof panels (See Figure 2) were obtained and each was subjected to one of the following conditioning procedures:

1. 50% relative humidity at 75 ± 2°F (24 ± 1°C) for five days.
2. 95% relative humidity at 75 ± 2°F (24 ± 1°C) for five days by storage in a fogroom with the panel draped with a plastic film to prevent the deposition of liquid water.
3. Complete submersion in a water bath at 75 ± 2°F (24 ± 1°C) for seven days and a subsequent nine day air drying period, under Procedure 1 conditions and without forced air.

Each panel was then subjected to flexural loading while in a horizontal position. The load was applied uniformly in 5 lb/sq ft (24.4 kgf/sq. m.) increments until failure occurred. Results are summarized below.

1. Panel conditioned at 50% RH and at 75 ± 2°F (24 ± 1°C) for five days. This panel failed at an equivalent live load of 135 lb/sq ft (658 kgf/sq. m.) with elastic load-deflection

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[2] 1 kgf = 9.806 newton.

behavior up to failure. Failure occurred when the compression skin buckled outward in a straight line transversely across the panel approximately six inches (15.2 cm) from, and parallel to, a splice in the honeycomb core.

2. Panel conditioned at 95% RH and at 75 ± 2°F (24 ± 1°C) for five days. This panel failed at an equivalent live load of 155 lb/sq ft (756 kgf/sq. m.) with elastic load-deflection behavior up to failure. Failure occurred as the compression skin buckled outward in a straight line transversely across the panel at a splice in the honeycomb core.

3. Panel submersed in water bath for seven days. Failure occurred at an equivalent live load of 104 lb/sq. ft. (508 kgf/sq. m.) apparently initiated by a fracture at a knot in the edge member as is shown in Figure 3. This was followed almost immediately by complete loss of load carrying capability as the compression sheet buckled in a straight line transversely across the panel at, and parallel to, a splice in the honeycomb core as shown in Figure 4.

   Water had entered the panel used in Test 3 during the soaking period at the wood edge members and traveled along the honeycomb sheet edges and splice. The panel weighed 207 pounds (94.0 kg) before placing in the water and 240 pounds (109.0 kg) on the day of test. The panel was taken apart after the test and the moisture content was determined on portions of the materials taken from an area which appeared to be the dampest portion of the panel. This area was at the intersection of the edge member and core splice. The moisture contents, listed below, are based on oven-dry (220°F, 104.4°C) weights.

Foam Insulation	129%
Honeycomb Core	41%
White Fir Edge Member	24%

The failure near, and parallel to, the core splice as shown in Figure 4 was typical for all three panels and shows inadequate adhesive bonding between the honeycomb and steel skins to the right of the core splice. This poor bond was apparently caused by a difference in the thickness of the two core pieces. This indicates a quality control problem when the core is spliced. As a result, it was recommended that either; (1) core splices be eliminated by using full length core sheets, or (2) core thicknesses be chosen and splices made such that the shear strength of the splice and that of the bond near the splice be equal to that of the honeycomb core without a splice.

These three flexural tests and observations made following the tests indicated that fillet forming properties and thickness of the adhesive were rather critical control factors in the manufacture of these panels. These tests also indicated that any loss in the adhesive bond strength with aging would be critical to panel performance. Therefore, additional small scale accelerated aging tests were conducted to evaluate the long term integrity of the adhesive bond in these panels.

3.2 System No. 2

System No. 2 housing units consist of glass fiber reinforced polyester (FRP) sandwich panels used in the ceiling (roof) and walls, while the floor is conventional wood construction. This system is illustrated in Figure 5. The FRP structural laminate facings for the walls, roofs and ceilings are about 0.08 in. (2.0 mm) thick and the FRP corrugated core is about 0.06 in. (1.5 mm) thick. All connections including that of the facings to the core and to the 2 x 4 plates are made with adhesives.

Structural evaluation tests were made on full-height wall panels and full length roof panels under short-term and creep loading conditions. These tests included axial compressive and racking (in-line shear) loading on wall panels and uniform, flexural loading on the roof panels. In general the test procedures were as described in ASTM Method E 72-68, "Standard Methods of Conducting Strength Tests of Panels for Building Construction" [4]. All the tests were conducted at normal laboratory environmental conditions, 75 ± 2°F (24 ± 1°C) and 50% RH.

The tests showed that the performance of the wall and roof panels would more than meet the requirements for short-term loading, but some doubts were raised for sustained loading. All failures in the wall panel tests were initiated due to failure of the adhesive bond between the 2 x 4 plates and the FRP facings. The shear load along these joints at failure averaged 20,300 lbs for two short-term compressive tests. Failures were observed in less than 60 days for the creep tests with applied shear loads of 6,000 lb. These tests illustrate the great differences which can be expected in the failure stress level between short-term and sustained loading on adhesive bonds.

Analysis of the results from the roof-panel, creep test and preliminary adhesive bond tests indicated that the bond strength between the roof panel facings and core is critical at roof temperatures expected in service, i.e. 80°F (45°C) above ambient.

As a result, additional testing of the adhesive bonds was performed in order to judge the effect of adverse environmental conditions and sustained loading.

4. Adhesive Evaluation

Many adhesives that are exposed to environmental conditions such as high humidities and elevated temperatures are known to undergo deterioration resulting in decreased bond strength. This process is referred to as aging and the speed of the aging process is frequently dependent upon the severity of exposure conditions. To evaluate the effect of environmental conditions on an adhesive bond by laboratory tests, the bonded materials usually are exposed to conditions more severe than those actually encountered in service on the premise that the more severe conditions will serve to accelerate the aging process.

4.1 Tests of System No. 1 Adhesive Bond

To assist in evaluating the steel-paper honeycomb sandwich panels of System No. 1 described previously, specimens were subjected to the ASTM Method C 481-62, "Standard Method of Test for Laboratory Aging of Sandwich Constructions" [2]. Cycle A of the test procedure was used and consists basically of 6 repetitive cycles of water soaking, steam spraying, freezing and dry heating. The specimens were tested for tensile and shear strength both before and after laboratory aging. The criterion for acceptable bond strength retention was that the aging test should not reduce the strength by more than 25 percent. ASTM Method C 297-61 [2], "Standard Method of Tension Test of Flat Sandwich Construction in Flatwise Plane" was used for the tensile test and ASTM Method C 393-62, "Standard Method of Flexure Test of Flat Sandwich Construction" [2] was used in determining the shear strength.

Specimens from the first sample submitted failed during the first cycle in the first step of the aging test [120°F (49°C) water soak for one hour]. The adhesive, based on poly(vinyl acetate), was somewhat water dispersible which led to delamination of the steel facings from the paper honeycomb cores. Specimens from later samples bonded with a neoprene-phenolic adhesive and with an epoxy adhesive proved to be satisfactory. Results of the tensile and shear tests for these two adhesives are summarized in Table 1.

4.2 Tests of System No. 2 Adhesive

4.2.1 Scope

The adhesive used to bond the core to the facings for the System No. 2 structural panels was evaluated to determine the effects of temperature, adhesive thickness, rate of loading, and sustained load on the bond strength and to estimate the expected durability. Lap panel specimens as shown in Figure 6 were cut from full size panels and tested in tensile shear at temperatures of 73, 105, 120, 150 and 180°F (23, 40, 49, 66 and 82°C). Specimens were divided into four groups according to the adhesive thickness at the lap joint. Several specimens from each group were tested at each temperature and the average values and the standard deviations computed.

4.2.2 Preparation of Specimens

Test specimens, 1/2 inch (1.27 cm) wide and 7 inches (17.8 cm) long, were cut from the facing-core bond area of the sandwich panels. Notches were cut in the specimens with a band saw in such a way as to provide a lap-type specimen with an effective bond area of 1/2 sq in (3.23 sq cm) in the lap joint. The notching technique is illustrated in Figure 6.

4.2.3 Test Procedures

The notched specimens were tested in tensile shear using a testing machine with the load being applied at a rate of 300 lb/min (136 kgf/min) in all tests, except the rate of loading studies. Those specimens tested at elevated temperatures were placed in the environmental chamber associated with the testing machine and allowed to equilibrate 30 minutes before testing.

4.2.4 Effect of Adhesive Thickness and Bond Strength

The adhesive thickness in the bond area of the lap joints varied from 0.01 to 0.20 in (0.25 to 5.0 mm). This variation occurred in specimens from within one panel as well as between panels. To effectively evaluate the adhesive bond, grouping of specimens according to adhesive thickness was necessary. The thickness increments chosen were: $<$0.04 in (1.0 mm), Group A; 0.04 - 0.08 in (1.0 - 2.0 mm), Group B; 0.08 - 0.12 in (2.0 - 3.0 mm), Group C; and 0.12 - 0.20 in (3.0 - 5.0 mm), Group D. The highest percentage of the specimens were in Group B.

The results of the data for adhesive bond strength versus adhesive thickness are presented in Figure 7 for test temperatures of 120, 150, and 180°F (49, 66, and 82°C). As expected, these data indicated that the adhesive bond strength decreased significantly with increasing adhesive thickness. Decreasing bond strength with increasing adhesive thickness had been noted in a previous study [5] using circular butt joints tested in shear.

4.2.5 Effect of Temperature on Bond Strength

Specimens tested at 73°F (23°C) did not consistently result in failure of the adhesive bond. At this temperature failure was observed in the FRP material, either by tension at notch B or by an interlaminar shearing within the FRP outer composite. Specimens tested at temperatures of 105, 120, 150, and 180°F (40, 49, 66, and 82°C) did result in failure of the adhesive bond interface.

The effect of temperature on the adhesive bond strength is presented in Figure 8. The adhesive bond strength decreased significantly with increasing temperature. Since failure at 73°F (23°C) was in the FRP, the actual adhesive bond strength is somewhat higher than the points plotted for 73°F (23°C).

4.2.6 Effect of Rate of Loading on Bond Strength

Additional specimens were tested in tensile shear at various rates of loading and at the temperatures used previously. The rates used were approximately 300 lb/min (136 kgf/min), 25 lb/min (11.4 kgf/min), and 2 lb/min (0.91 kgf/min). Figure 9 illustrates the effect of the various loading rates upon the observed failing load.

The modified Prot method described by Boller [6] was applied to the rate of loading data in an attempt to obtain an estimate of the endurance limit. The application was unsuccessful, however, as the resultant curve did not intersect the ordinate in a positive region as required by the method.

4.2.7 Effect of Sustained Loading on Bond Strength

In order to estimate the expected endurance limit of the adhesive bond, specimens of thickness Group B were subjected to a stress-rupture test. Various sustained static loads were placed on the specimens and the time to failure measured. The sustained loads used were 100, 60, 50, 40 lb (45.4, 27.2, 22.7, 18.2 kg). The test results are plotted in Figure 10. Other points are being obtained at the present time to obtain a more accurate estimate of the endurance limit. An extrapolation of the existing curve to 10,000 hours yielded an estimated endurance limit of approximately 30 lbs (13.6 kg).

5. Summary

A brief description of some of the "Operation BREAKTHROUGH" structural evaluation tests has been presented.

Results from some of the adhesive bond tests for two sandwich-panel systems are presented.

Use of the accelerated aging method of ASTM C-481 indicated the need for a better adhesive than that used in the original sample of System No. 1. As a result, a different adhesive, meeting the requirements of this test, was used.

The results from adhesive bond tests for System No. 2 indicated that: (1) the strength of the adhesive bond decreased significantly with an increase in adhesive thickness; consequently control of the thickness is obviously an important quality control factor, and (2) in the design of the structural components the expected maximum service temperature of the adhesive and the magnitude of the sustained stress must be considered because the sustained-load strength under expected service temperature is much less than that indicated by short-term, room-temperature test results.

6. References

[1] Leyendecker, E. V., A General Overview of Operation Breakthrough, (This paper included in this Proceedings).

[2] 1971 Annual Book of Standards, Part 16, American Society for Testing and Materials, Philadelphia, Pennsylvania.

[3] Performance Specification for for Adhesives for Field Gluing Plywood to Wood Framing, AFG-01, American Plywood Association, Tacoma, Washington, 1969.

[4] 1971 Annual Book of Standards, Part 14, American Society for Testing and Materials, Philadelphia, Pennsylvania.

[5] Bryant, R. W., and Dukes, W. A., "The Effect of Joint Design and Dimensions on Adhesive Strength", Structural Adhesives Bonding, Edited by Michael J. Bodnar, Interscience Publishers, New York, New York, 1966.

[6] Boller, K. H., "Application of Prot Test Method to Stress-Rupture Curves of Glass-Reinforced Plastic Laminates", Forest Products Laboratory Report #2118, Madison, Wisconsin, September 1958.

TABLE 1. Tensile and Shear Strength of Adhesives for System No. 1

Adhesive		Tensile Strength[1]		Shear Strength[2]	
		Not Aged psi	Aged psi	Not Aged psi	Aged psi
Contact[3] - 1		31.5	32.2	27.1	22.1
" 2		33.8	26.0	28.9	23.3
" 3		33.5	32.6	28.7	22.8
" 4		28.0	31.4	--	--
" 5		27.0	31.6	--	--
	Avg.	31.0	31.0	28.3	22.7
Epoxy - 1		36.3	22.6	23.8	17.9
" 2		26.3	23.0	23.5	20.5
" 3		38.8	28.3	24.9	21.0
" 4		46.3	23.1	--	--
" 5		31.6	39.7	--	--
	Avg.	35.9	27.3	24.1	19.7

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[1] 4 in. x 4 in. specimens tested by ASTM C-297 (2). Failure was in the adhesive-facing bond for all contact adhesive specimens. Failure was in the core for all unaged epoxy specimens, but was in the bond between the wash coat primer and the metal facing for the aged epoxy specimens.

[2] 6 in. wide specimens tested by ASTM C-393 (2) on an 18 in. span with the honeycomb core paper ribbons parallel to the width of the specimen ("W" direction). Failure was in the core for all specimens. Differences noted between adhesives are due primarily to variability in the shear strength of core from different lots.

[3] Neoprene-phenolic adhesive,

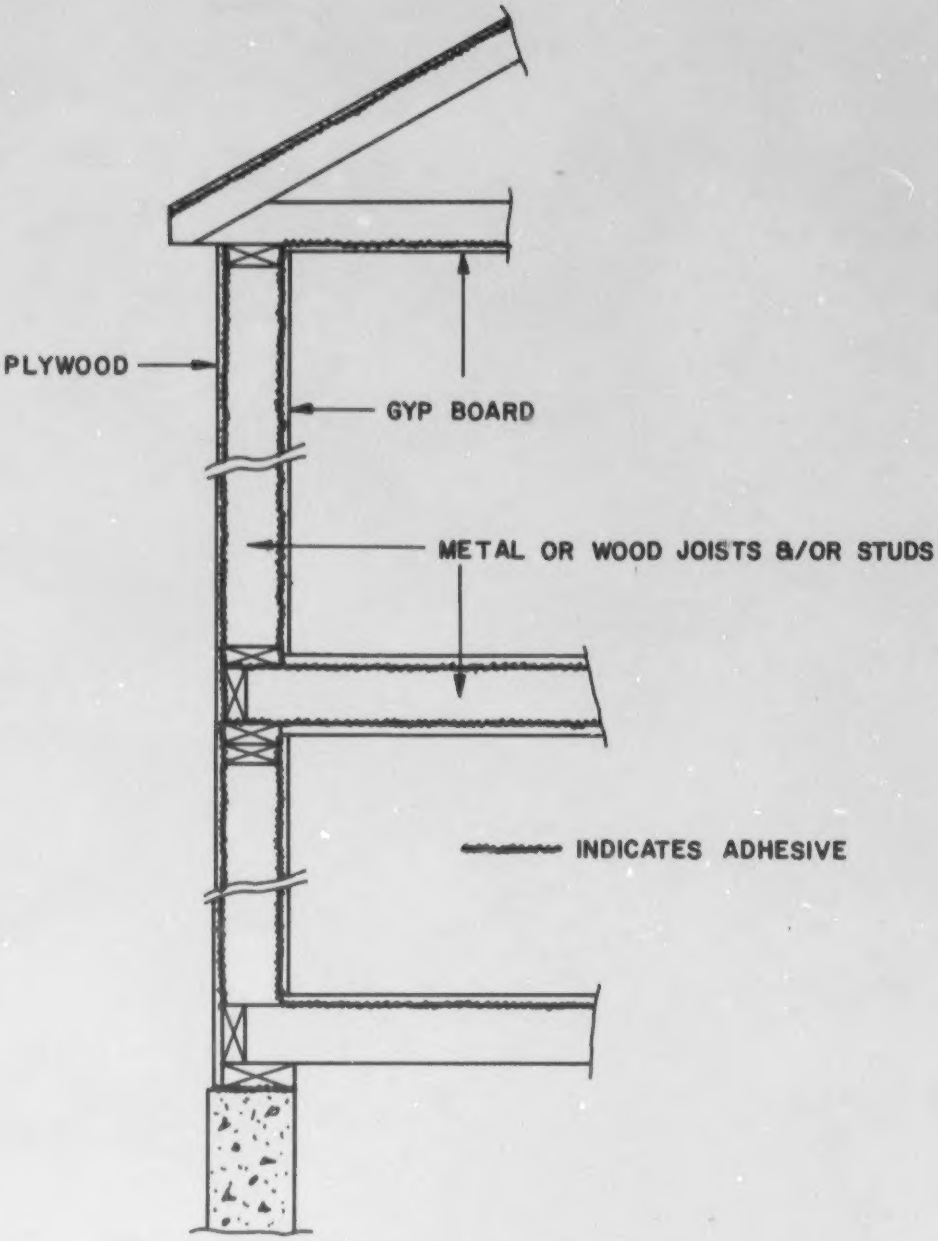

PLYWOOD
GYP BOARD
METAL OR WOOD JOISTS &/OR STUDS
INDICATES ADHESIVE

FIGURE 1. Typical adhesive applications in framed housing systems.

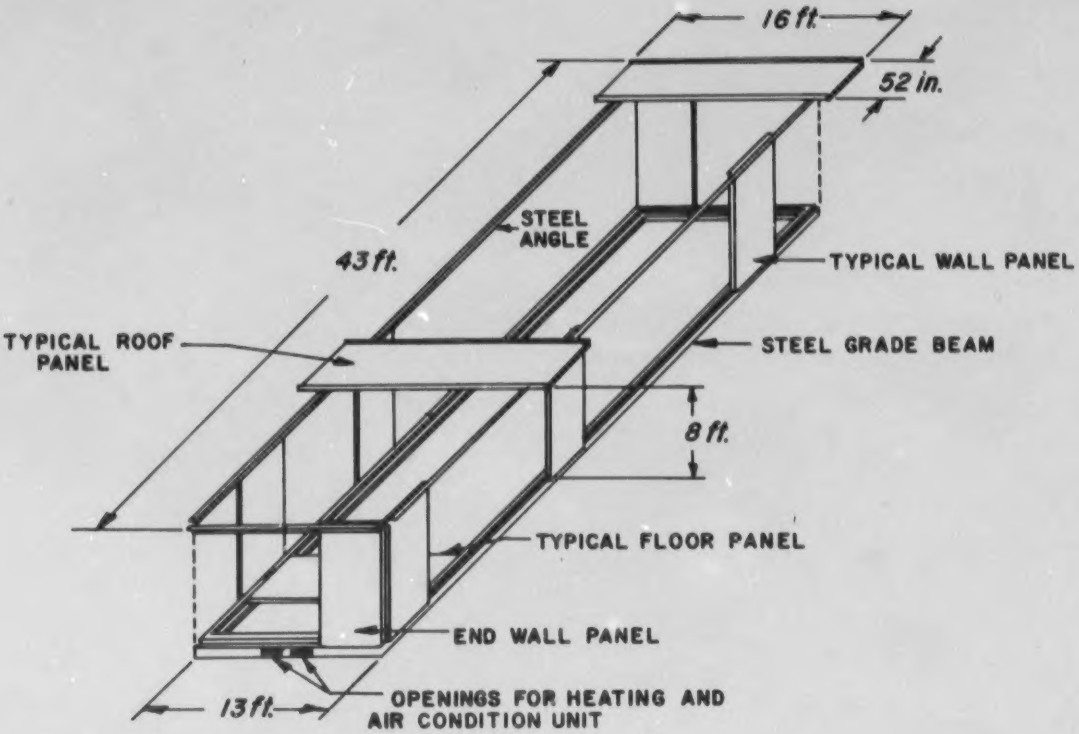

16 ft.
52 in.
43 ft.
STEEL ANGLE
TYPICAL WALL PANEL
TYPICAL ROOF PANEL
STEEL GRADE BEAM
8 ft.
TYPICAL FLOOR PANEL
END WALL PANEL
13 ft.
OPENINGS FOR HEATING AND AIR CONDITION UNIT

FIGURE 2. Structural isometric of System No. 1.

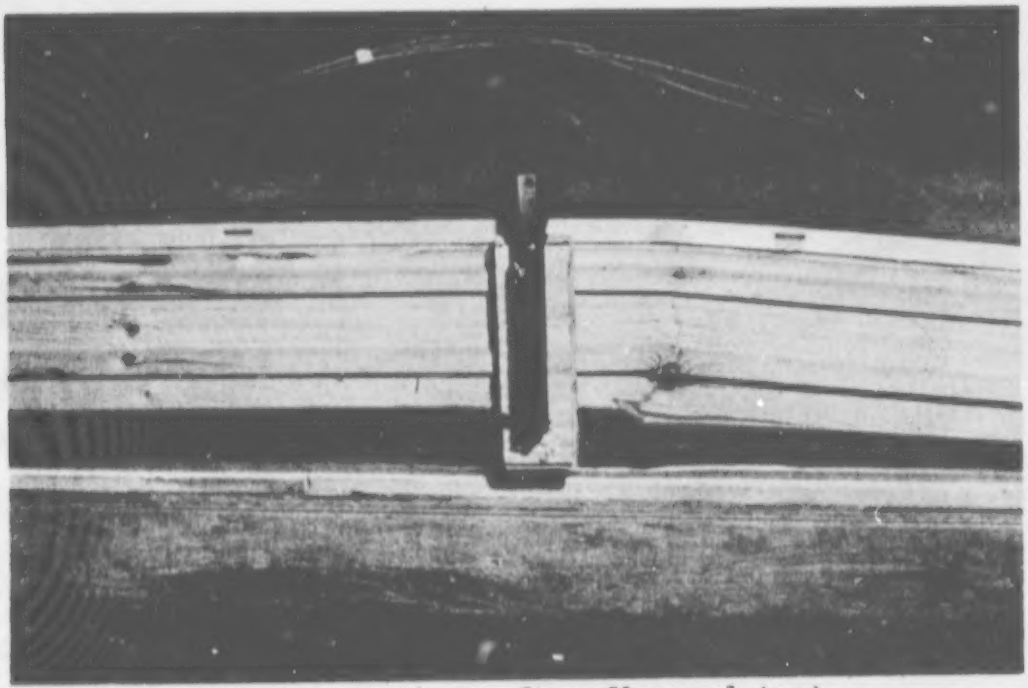
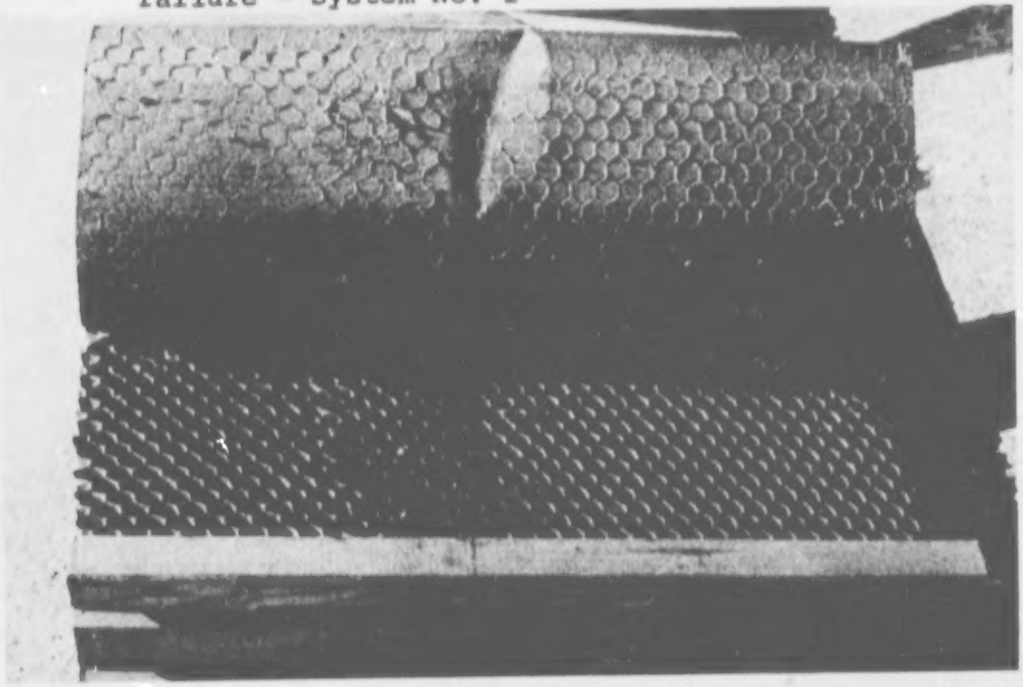


Fig. 3 Roof panel specimen after flexural test - System No. 1

Fig. 4 Roof panel material at location of a typical failure - System No. 1



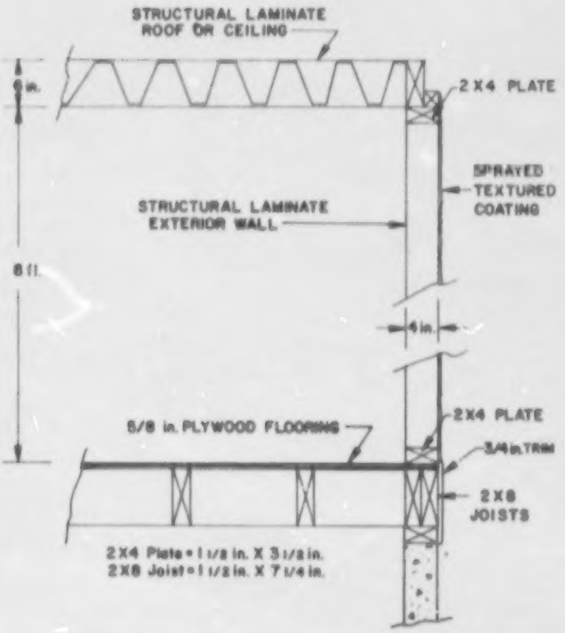

STRUCTURAL LAMINATE ROOF OR CEILING
6 in.
2 X 4 PLATE
SPRAYED TEXTURED COATING
STRUCTURAL LAMINATE EXTERIOR WALL
8 ft.
4 in.
2 X 4 PLATE
5/8 in. PLYWOOD FLOORING
3/4 in. TRIM
2 X 8 JOISTS
2 X 4 Plate = 1 1/2 in. X 3 1/2 in.
2 X 8 Joist = 1 1/2 in. X 7 1/4 in.

FIGURE 5. System No. 2 structural section.

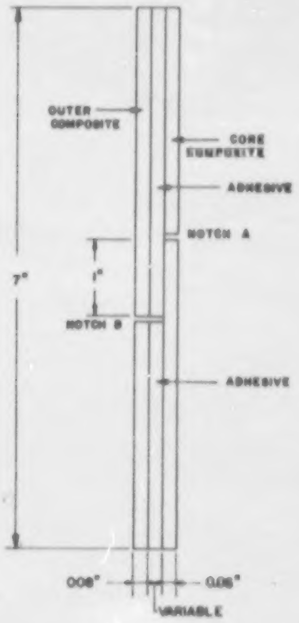

OUTER COMPOSITE
CORE COMPOSITE
ADHESIVE
NOTCH A
1"
7"
NOTCH B
ADHESIVE
008"
0.06"
VARIABLE

FIGURE 6. Tensile shear specimen cut from roof or wall panel - System No. 2.

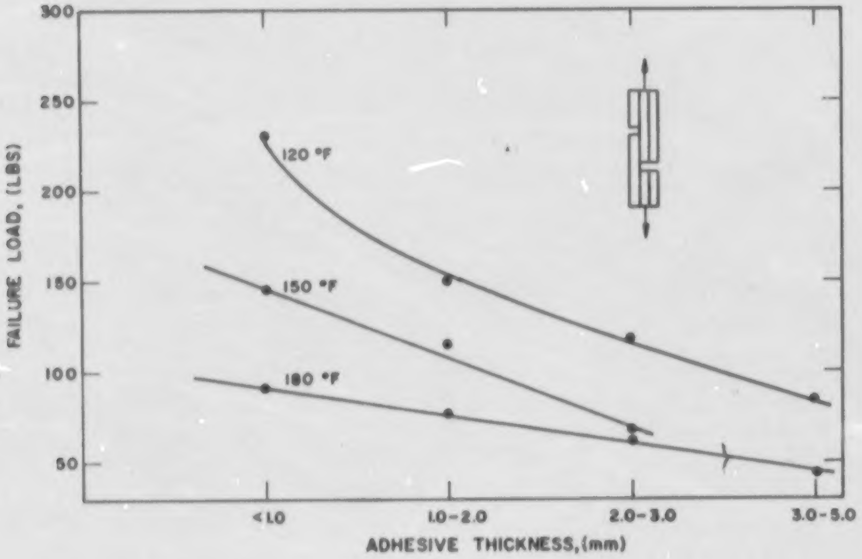


FIGURE 7. Effect of adhesive thickness on shear strength of bond - System No. 2.

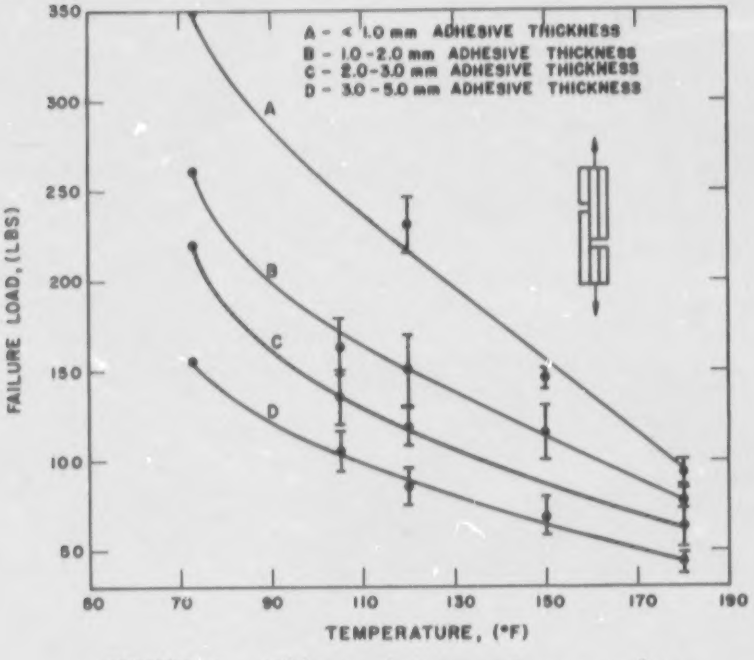


FIGURE 8. Effect of temperature on shear strength of bond - System No. 2.

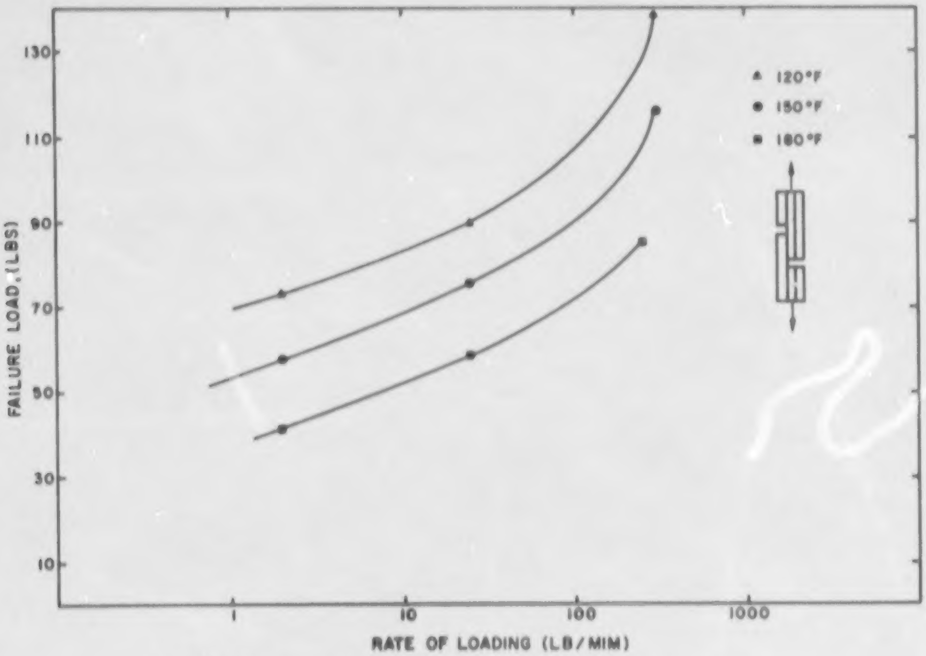


FIGURE 9. Effect of loading rate on shear strength of bond - System No. 2.

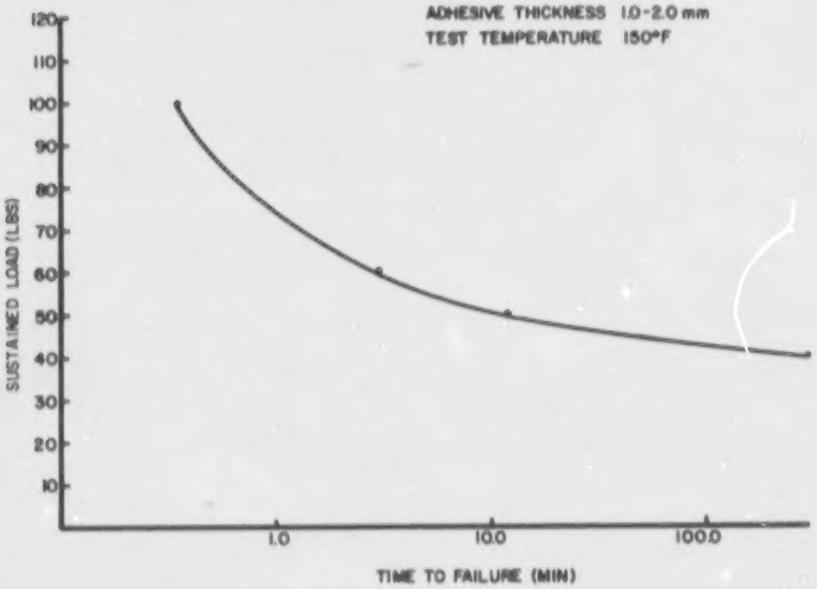


FIGURE 10. Effect of sustained loading on shear strength of bond - System No. 2.

National Bureau of Standards Special Publication 361, Volume 1: Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium, held May 2-5, 1972, Philadelphia, Pennsylvania (Issued March 1972).

Performance Requirements for Bituminous Roofings

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Factors related to performance of the shingle and the built-up membrane bituminous roofings are discussed under the general headings of durability, roof traffic considerations, appearance and economic evaluation. Durability relates to resistance to weather including wind and hail, and ability to withstand stresses within the membrane such as caused by thermal and moisture changes and by differential membrane and deck movements. Additional testing of roofing systems for ability to withstand movements is suggested and research methods which seem adequate are cited. Testing and requirements for fire resistance and hazard are described. Model analysis and testing are suggested to determine parameters and properties of materials required to be able to design properly performing traffic decks. Appearance is a primary design consideration for strip and individual shingles, whereas membrane systems mostly are applied for protection only. If a non-black appearance is desired, surfacing of the membrane with aggregate or a coating is feasible and additionally can improve durability. A method of economic analysis to determine the annual cost of a roof over its projected life is proposed. This includes in addition to first cost and annual capital charge, terms for maintenance, and the cost of surface renewal modified by a present worth factor. Quality control of the component parts and in application are key factors, once an adequate design of a roof system has been determined. Bituminous roofs can be varied greatly in design, and with proper care in construction will provide long time satisfactory performance at minimum cost in comparison with other systems.

Les facteurs relatifs aux performances de bardeaux et des couvertures à membrane bitumineuse rapportée sont discutés sous les rubriques générales suivantes: durabilité, considérations de trafic sur le toit, apparence et coût. La durabilité est liée à la résistance aux intempéries, y compris le vent et la grêle, et à la capacité de supporter les tensions causées dans la membrane par des variations thermiques et hydrométriques et par des déplacements différentiels entre la membrane et son support. Un essai supplémentaire de la capacité de résistance aux mouvements est suggéré et les méthodes de recherche. Les essais et les exigences relatifs à la résistance au feu et aux dangers d'incendie sont décrits. Une analyse de modèles et des essais sont suggérés pour déterminer les paramètres et les propriétés de matériaux pouvant être utilisés avec sûreté sur les planchers recevant du trafic.

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[1] Consulting Bituminous Engineer

L'apparence est primordiale pour des bandes et bardeaux individuels alors que les systèmes à membrane sont appliqués le plus souvent, en protection. Si l'on désire une autre couleur que le noir, la membrane peut être recouverte d'agrégats ou d'enduits, ce qui en augmente la durabilité. Une méthode d'analyse économique est proposée pour déterminer le coût annuel d'un toit compte tenu de sa durée de vie prévue. Ceci comprend, en plus des premiers frais et de la charge financière annuelle, des provisions pour l'entretien, le coût de renouvellement de surface celui-ci étant modifié par un facteur d'actualisation. Le contrôle de la qualité des composants et de leur application sont des facteurs essentiels une fois que la conception d'un système de toiture a été adopté. Les toits à base de bitume peuvent être de conception très variée et, s'ils sont construits avec soin, ils donneront très longtemps satisfaction pour un coût minimum comparé à d'autres systèmes.

Key words: Bituminous; cost; durability; performance; roof behavior; roofing.

1. Introduction

Of the total roof areas in the United States, the bituminous types of coverings are by far the most common, with some estimates being that they constitute as high as 85% of the total roof areas, even though locally other roofings may predominate. Bituminous roofings fall into two main categories: the built-up membrane, and the individual and strip shingle types. Shipments of asphalt and tar roofing products during 1970 are given in Table 1. From these shipment values, a very approximate estimate would be that the shingled area was perhaps 25% greater in 1970 than that of the built-up bituminous roof, assuming the latter to be mineral surfaced or a base sheet with three plys of felt.

The bituminous roof system may be as simple as a covering over a deck, but usually the built-up roof additionally includes roof insulation. In large buildings, the built-up membrane roofings are continuous over wide expanses and must withstand large lateral forces between joints, these forces being produced by building, insulation and deck movements as well as differential movements from temperature changes and from moisture content changes within the membrane. Interply bonding strength and the bond of the membrane to the deck or insulation are important. The strip and individual shingle, in contrast, consist of discrete units, each held in place by spot fastening at the top (head-lap) and usually at the base of the exposed area (butt) by a seal-down adhesive.

Because of the basic construction difference in shingle and membrane roofings, the acceptable slope to prevent water entry to the deck differs greatly. The built-up membrane has been used from dead level to steep slopes, although the minimum recommended to prevent ponding of water usually is 1/4" per foot. Shingles usually are not recommended to be applied to a slope of less than 4" per horizontal foot.

Thus, it is seen that even if the weather exposures might be the same, the forces which the roofings must withstand are quite different for the two types. Herein, an effort is made to examine some of the properties required to have effective performance of bituminous-based roofings.

2. Durability

2.1 Movements in Roof Membranes

There seems to be little doubt that performance of roofing membranes can be related directly to thermal and particularly to moisture induced movements in the membrane. If these movements are spread evenly over the total area, the strain becomes much less and seems largely recoverable; however, over joints and cracks the elastic limit readily can become exceeded to cause splitting or wrinkle cracking. Recent findings on causes and extent of lateral movements are reviewed briefly.

Martin (1), in his study on membrane rupture failures, estimated movement rates to be very low, and from his data to correspond to about 0.2% per hour. He considered the maximum temperature change to be 1°F. per minute. In spite of the low rate of movement, he concluded that the elastic limit can become exceeded, and with repeated cycles of straining the strength of the roofing membrane decreases markedly. Single extension tests on asphalt-impregnated fabrics were considered to have little meaning in relation to in-use performance. To simulate actual roof membrane movements, Martin devised a moving joint tester, the movement being provided by expansion and contraction of an inverted aluminum chanel painted black and exposed to move with daily variations in temperature. The lives before tensile failures of the exposed membranes, 2" x 12" strips fastened over the joint, were found to vary greatly, from three to greater than thirty-six months. Spot attachment, or a one-inch loose bond at the joint, increased the life of a particular membrane severalfold.

Koike (2) tested twelve types of roofing membranes for fatigue rupture, varying both the joint movement and temperature in his cycling, conditions becoming more severe as the test continued. He classified membranes according to the amount of joint movement they could be expected to stand without splitting failure. His cycles, 300 being carried out in 20 hours, varied in total movement from 0-0.25 mm to 0-10.0 mm and in temperature from 60° to -30°C. The number of cycles completed were as high as 13,500. He advised that asphalt-based membranes and fluid-applied synthetic membranes could not be expected to withstand movements greater than 0.5 mm.

Cullen and Boone (3) concluded that their laboratory determined thermal factor, if utilized, should reduce potential failures in service from splitting. They recommended that a membrane with a higher factor would be required for climatic areas with lower temperature, and for membranes placed over thermal insulation. The latter application results in more rapid temperature changes than if the membrane is placed directly on the deck, which can act as a heat sink. Their thermal shock factor, TSF, is:

$$\frac{\text{Breaking load of the membrane}}{\text{modulus of elongation X apparent linear thermal expansion coefficient per }^{\circ}\text{F.}}$$

where modulus of elongation = load on 1" strip divided by strain

None of the foregoing authors considered the effects of moisture, and this remained for Brotherson (4) and Shuman (5), especially, to study in detail. Brotherson showed that moisture accumulations in saturated felts could produce blistering and wrinkling. Shuman found that moisture effects were large and could override thermal effects in organic felts, with both, however, playing a part. Moisture in asphalt saturated felts can occur in two locations - interstitial and intracellular. Ridges developing in roofing membranes were found to persist for months because vapor-pressure differentials did not permit intracellular drying. Equilibrium moisture content of organic felts in particular depends upon relative humidity in the particular area, and this explains why moisture pick-up can cause felt expansion under lowering temperature conditions.

Long (27) determined that dimensional equilibrium in roof membranes would be slowly if ever reached, moisture effects being highly variable and in many cases overshadowing charges from temperature.

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1 Figures in parentheses indicate the literature references at end of this paper.

Tater and Alexander (7) found that, even through moisture-vapor transmission rates through roofing membranes might be considered negligible, slow transmission into membranes could in time saturate the felts, and with proper conditions become free moisture. Free moisture with temperature increase can develop appreciable pressures to cause blisters and/or interply delamination. They presented evidence that moisture accumulation during late fall and winter seasons exceeds the amount the system can accommodate during the following summer season.

Comments

With respect to thermal and moisture content changes and ability of roofing systems to withstand resulting movements, there would seem to be much room for additional research to develop more durable systems. The experimental methods of Koike (2) and of Martin (1) seem valuable to evaluate materials and systems, including different methods of bonding to substrates. Very great difference in resisting splitting was shown by the various systems tested. In particular, modified bitumens would seem desirable to permit strain adjustment at low temperatures without having failures at joints or cracks. The procedure of Cullen and Boone (3) for determining thermal shock factors also can be used for investigation of modified bituminous systems and predicting their resistance to splitting.

Quality factors, both in manufacture and installation, seem to be the most important in minimizing blistering, interply delamination and wrinkle cracking, since quality of both can influence greatly the extent of moisture and thermal movements. Increased saturation of felts, even above Underwriters' limits, would reduce the rate of moisture pick-up. The Technical Committee of the Asphalt Roofing Manufacturers' Association considered tests to measure water pick-up by base and cap sheets. Such test methods, once developed and standardized, would provide far better quality in manufacture, with reduced pin-holes and holidays in both top and back coatings of roll roofing and shingles. Asbestos and glass felts, while less susceptible to moisture pick-up, have been shown to be more prone to splitting under high thermal shock conditions (3). Good engineering design requires strict attention to provide sufficient and adequate joints and flashings to oppose the effect of temperature and moisture movements (8). The lower strength of organic felts in the across machine direction should always be recognized in directional roof placement and joint locations.

Shuman (5,6) decrys the term "vapor barrier", and suggests instead the term "vapor retarder", since sheet materials, coatings and adhesives do transmit moisture vapor and even if at a very low rate saturation of the felt eventually can occur. Tater and Alexander (7) confirmed this moisture movement. Shuman's rule is, as far as practically possible, to install a DSIM system: deliver dry, store dry, install dry, and maintain dry.

Recommendations would seem to include additional experimental investigation of the engineering properties of different roof systems to determine their performance under lateral and interply movement forces, and careful control of all quality factors of roof system components.

2.2 Weather Resistance

Weather resistance, as apart from forces causing lateral and interply movements from temperature changes, moisture and wind, is primarily the resistance to sunlight degrading factors, surface movements such as can cause loosening of roofing granules, pattern cracking, and the effects of water, frost, and ice on the roof system. Air pollution factors sometimes can cause severe effects. Hail, wind, and fire resistance are treated separately.

Control of degradation by sunlight is quite well understood, that is, to have a mineral or pigmented surfacing to prevent all or nearly all entry of ultra-violet light to the asphalt or tar surfacing. There are only a few sources of suitable base rock or minerals for the manufacture of granules, most deposits lacking opacity or other qualities. To illustrate how specialized the field is, 19 recommended test methods for granules have been developed. (9). With built-up roofings, selection of the gravel or slag covering is less critical, since the greater thicknesses of covering prevents light transmission to any appreciable degree.

Selection of asphalt saturants and coatings for all roofings is important. Physical properties, weatherability and compatibility of saturants and coatings all play a part in durability. Table 2 lists typical ranges of properties desired.

The Underwriters' Laboratories have standards for composition and make-up of Class C Asphalt Organic-felt Sheet Roofing and Shingles (11); however, weather resistance requirements are not included, although it is recommended that the "granule mineral surfacing be sound, durable, and substantially opaque to ultra-violet light."

Mineral stabilizers commonly are added to the coating asphalts in amounts up to 55% by weight of the stabilized coating. A study showed that selection of the mineral stabilizer and its properties are important in determining the weather resistance of the filled coatings (10).

Roofing manufacturers carefully evaluate raw materials used in roofings and, in addition to accelerated weatherometer testing, strongly believe in long-term outdoor exposure to give follow-up information.

Comments

Weather resistance of bituminous-based roofings is seen to depend largely on selection and quality control of the separate components. While accelerated weatherometer tests are used, their results are chiefly used as quality controls. Much dependence is placed upon knowledge of the past performance of the components making up the roofing. Natural weather exposure observations are made, and results of exposures are carefully viewed to monitor the success of quality control tests. Field complaints are studied carefully to determine if any trends in performance are developing.

A disturbing factor is that the pipe line and tanker crude sources for asphalts in present refinery practice constantly are changing, and the quality likewise can change. Four laboratory methods for predicting the durability of roofing asphalts have been suggested, and such procedures become more and more important to insure the proper performance of bituminous roofings (12).

A number of roof slippages have occurred in different parts of the country, particularly in the South and Southwest. The possible reasons much discussed include a defect or defects in basic specifications for roofing asphalts, a lack of quality control in the manufacture of the asphalts, or lack of adequate quality control and supervision in the construction of the built-up roof membranes. At any rate, it is known that some asphalts drop back in softening point more than others on heating to application temperatures, and some purchasers of roofing asphalts are specifying and others considering a laboratory heat test to measure this tendency. This test, which generally is considered too severe by roofing asphalt manufacturers, is to heat the asphalt in a closed container at 550° F. for five hours. The maximum drop-back desired in softening point is 0 to 15° F., dependent upon grade. Additionally, a test to determine flow tendency at 140° F. of asphalts subjected to the heat test is being evaluated.

2.4 Wind Resistance

Wind damage can result in large economic loss. Both Factory Mutual and the Underwriters' Laboratories (13,14,15) recognize this and require difficult wind uplift requirements for membrane systems which must be met to qualify for an FM Class I rating on steel decks, or an Underwriters' rating for a specified roof deck construction. The test methods of both laboratories, while similar in that the roof covering is subjected to increased wind pressures, differ in detail. Factory Mutual requires there be no separation of any bond between the metal roof deck, vapor barrier, or insulation at forces up to and including 60 psf. There also shall be no delamination of the insulation board required in the test. Underwriters' use both steady state and oscillating pressures to simulate the effect of wind gusts. The tested roof deck constructions are classified as Class 30, Class 60, or Class 90, the classes being the maximum uplift pressure in psf imposed on the test assembly specified by the manufacturer.

Underwriters' requirement (16) for wind resistance of prepared roof-covering materials is applicable to coverings which comply with the requirements for Class A, B, or C fire resistance. Wind resistance of prepared roofings usually is obtained by utilizing a factory applied tab adhesive or an interlocking construction. The test panel with the temperature conditioned shingles, at a specified elevation to the horizontal, is subjected to winds at a velocity of 60 miles per hour for two hours at 75° F. During this time, the shingles shall not lift from the adhesive, or the locking ear or tab tear loose or disengage from its locking position. Also, a free portion of a shingle shall not lift to stand upright or bend back on itself.

Comments

Wind uplift resistance is measured with laboratory controlled wind uplift forces, and test results have seemed to correlate very well with field performance. The success of the sealed-down shingle in preventing wind damage has been observed many times. An area for further development in adhesives would be to improve their performance under adverse time-temperature conditions, and under dust conditions before sealing occurs.

2.4 Hail Damage

Hail is a weather phenomena occurring mainly in the Midwest in the states between the Appalachian and Rocky Mountains. The destructive effect of hail has been investigated in the laboratory by Greenfeld (17). His findings showed that the impact energy reached by 1-1/2 to 2 inch diameter hailstones was sufficient to damage most roofing materials. With bituminous roofings, heavier shingles, the more solidly supported roofings, and those with coarse aggregate surfacings showed improved resistance to hail damage.

Comments

Tests made at higher temperatures seemed definitely to show improved resistance to hail damage (17). Determination of the performance of bituminous coatings with lower viscosity-temperature susceptibility would seem to be a desirable research investigation. Also, since roof constructions with inorganic felts showed more resistance than those with organic felts, investigation of various types and heavier weight of carrier sheets for bituminous roofings would seem promising.

2.5 Fire Resistance and Hazard

The standards for fire resistance and hazard differ for bituminous membrane and for shingle roofings. Also, the test methods to determine the fire hazard of membrane roofings by the two insurance rating laboratories differ. Chief concerns in fire hazard are the rapidity of spread of flame from fuel contribution within the building, and the behavior of the roof covering itself.

Factory Mutual (18), with requirements for membrane roofing over steel decks, developed a calorimeter test in 1955 after the disasterous Livonia, Michigan industrial fire which was considered to have spread rapidly from molten asphalt drippings. With non-combustible decks which will not burn or contribute fuel to the fire, while preventing passage of heat through the deck from either side, Factory Mutual permits any combination of above deck materials without the need for automatic sprinkler protection. Such construction receives their non-combustible rating. Their Class I rating applies to roof deck material over steel decks which burn slowly and with fuel contribution reduced to acceptable limits by selection of a proper combination of above-deck materials. Wind uplift resistance of 60 psf, previously discussed, also is required for a Class I rating. A passing calorimeter test is based on the fuel contributed value being 200 BTU per ft.^{2} per minute maximum under standardized conditions. This results in a fuel contributed index of 100, considered equivalent to a flame spread index of 25 in the ASTM E-84 large tunnel. Thus, the Factory Mutual procedure relates to rate of spread of flame within the building.

The Underwriters' Laboratories have two very distinct procedures: one for roof deck constructions relating to spread of flame beneath the deck, and another for test of fire resistance of roof covering materials. The test for roof deck constructions utilizes the ASTM E-84 (19) tunnel, and the standard requires the flame spread to be not greater than that of a roof deck construction consisting of a steel deck, without vapor barrier or adhesive, insulated with a one-inch thick plain vegetable fiberboard mechanically attached and covered with a standard 4-ply built-up roof covering with gravel surfacing. Constructions specified by the manufacturer with various components, as vapor barriers, adhesives, insulations, and roof coverings are listed as Fire-Acceptable if such a flame spread requirement is met. The roof deck construction may or may not also be rated for wind uplift resistance.

Underwriters' Laboratories rate the "Fire Resistance of Roof Covering Materials" (20) as complying with requirements for one of three classes: A, B and C. Class A roof coverings are effective against severe, B against moderate, and C against light fire exposure. The ratings depend upon withstanding specified conditions developed by burning wood brands, intermittent flame, and spread-of-flame tests. Class C requirements usually are met by standard shingles.

Plastic foam materials represent a special case if used in roof constructions, since they can collapse when heated. The Factory Mutual test for "Susceptibility to Heat of Cellular Plastics" is carried out in a test furnace, and requires the material to show little or no visible damage as compared with that sustained by plain wood fiberboard roof insulation tested under the same conditions. This is in addition to other required tests for Class I rating. If Class I rating is not obtained, a Class II rating is assigned (23).

Additionally, both laboratories rate roof-ceiling constructions in terms of hours of fire resistance under the requirements of ASTM E-119, "Standard Fire Test of Building Construction and Materials" (21,22). The built-up roof coverings used in the assembly construction can meet either the Class A, B or C requirements for fire resistance.

Comments

The tests for fire hazard and fire resistance appear to be solidly based on the performance concept. Factory Mutual states flatly that the fuel contribution rate of a combustible material has been shown by fire tests to be the single most significant property for predicting its flame spread potential. Additionally, the FM Research Corporation reported that on a series of 50 fire tests with the FM construction-materials calorimeter, on materials having a known flame spread rating from the ASTM E-84 tunnel test, they were found to have fuel contribution rates which compared favorably with their flame spread ratings (18). The FM index of 100, or flame spread index of 25, was based on results of large scale fire tests conducted in a building 100 feet long by 20 feet wide.

3. Other Considerations

3.1 Roof Traffic Resistance

Damage from traffic can occur during construction or with subsequent casual or intensive traffic usage. Use of overlays and construction requirements and hazards for protection against foot traffic have been described (24). Design of a roof deck serving for automobile parking requires much more special bed considerations, and there seems to be no satisfactory standardized design utilizing bituminous materials or combinations. Within the layered system usually employed (25), special forces react on the membrane, both from the traffic surface and the roof deck. Such forces can cause interply delamination or disruptive tensile failures.

A specialized type of traffic might be considered ponded water. Roofs are used for collecting water in a number of areas, notably the Caribbean, but ponding such as practiced for the heat insulating and cooling advantage has a number of built-in disadvantages, such as leak potential and difficulty in locating interply delamination and potential bacterial deterioration. Constructions other than bituminous are recommended for ponded roofs.

Comments

Investigation is needed badly in determining proper methods of design and construction for traffic decks. Simulated mathematical-mechanical models are possible with their solution based on modern computer technology. Proper membrane protection of bridge decks is an allied problem. Isolation of the membrane by layers capable of support, but also capable of strain relief at maximum rate of stress as produced by temperature change extremes and deck movements, would seem to be a logical approach to obtain satisfactory performance.

3.2 Roof Appearance

The styling of shingles, both as to color and texture, is highly important as a sales feature, since the majority of dwelling roof areas are visible. In contrast, only limited areas of the membrane type of roofing require a surface covering designed for esthetic performance.

Shingle appearance depends upon selecting mineral surfacing for the color, with the texture being obtained from the granule size and gradation, or by other means as double coverage of granules, embossing, and fold-overs. Membrane roofings in some instances are covered with mineral surfacings selected for their appearance, among other properties, but in free-form roofs appearance largely is obtained by application of color coatings, such as aluminum pigmented asphalt coatings through all of the variety of pigmented products suitable for application over bituminous roofings. Satisfactory performance of surfacings, whether mineral or organic, depends largely on opacity to ultra-violet light, together with compatibility and good bond to the bituminous surface. The organic coatings also must resist shrinkage from loss of plasticizer to prevent a crack pattern and curling from developing over a reasonable time, say for at least two years. Excessive chalking also is undesirable, and can discolor building walls.

Comments

Satisfactory and pleasing roof appearance seems to present no particular problems in design. Manufacture of shingles at reasonable cost can be a problem if their design is complicated. Properties required in mineral surfacings are well understood, and quality tests are available. Less well understood are the requirements for organic coatings, based on synthetic polymers, for use over membrane roofings. Their suitability must be determined by trial formulations, followed by laboratory and by field testing under the variety of climatic conditions expected in service.

4. Economic Evaluation

A method of determining the annual cost of a roof over its projected life is useful in comparing the expected costs of different constructions. As proposed here, the economic analysis is made only on the roof covering itself, either the membrane or shingle type. This includes expansion joints, vents, flashings, gravel stops and such other features that are part of the completed roof covering. The insulation, vapor barrier and roof deck normally would not be considered, excepting in that they may change the expected life of the roof covering. This method is an adaptation of a method proposed for estimating the annual cost of highways (26), and includes the following items, all values being based on a roof area of one square (100 square feet):

A is the first cost.
M is the maintenance cost. This is not the cost of resurfacing projected in the future, which is treated separately, but would cover the expenses in localized repairs on the covering and components.
E_1, E_2, etc. designate the costs of surface renewal, which are spaced over the life of the roof.
r is the interest on the first and subsequent renewals.
n is the analysis period selected to represent the life of the

roof, commonly 10, 15 or 20 years.
y is the number of years between the time of last roof surface renewal and the end of the selected analysis period.
x is the estimated life in years of the last surface renewal.
CRF is the annual capital charge or recovery factor and is

$$\frac{r(1+r)^n}{(1+r)^n-1}$$

PWF is the present worth factor and for a single payment is

$$\frac{1}{(1+r)^n}$$

C is the total annual cost per roofing square, and is

$$C=CRF\,[A+E_1(PWF_1)+E(PWF)-(1-\frac{y}{x})(E_1 \text{ or } E_2)(PWF_1 \text{ or } PWF_2)]+M$$

For example, assume a membrane roof at an initial cost of $7.00 per square, interest at 7% annual, and a 10-year life.

$$CRF_{10}=0.143$$

Assume a surface coating required after five years, costing $2.00 per square, and that this will maintain the roof to the end of the analysis period.

$$PWF_5=0.51$$
$$C=0.143[7.00+2.00\ (0.51)-(1-\frac{5}{5})(2.00)\ 0.51)]+0=\$1.15/\text{yr.}$$

5. Conclusions

Satisfactory performance of bituminous-based roofings depends upon an understanding of the engineering properties required in their design and construction. This is necessary together with watchful quality control of the guideline properties of all of the components, and also in roof construction. The central factors and property requirements of the components going into the roof construction largely are based upon hard won past experience.

Additional exploratory studies are needed to develop membrane roof systems which will withstand more rigorous conditions without failure from movements caused by moisture and temperature changes, or by moving cracks and joints. The rheology of bitumen-synthetic polymer combinations for coating and bituminising fabrics has been little explored, and would seem to offer a logical approach to obtain systems with better elastic recovery properties and better resistance to effects of temperature changes.

Organic felts are known to have serious deficiencies with regard to change in dimensions with change in moisture content, with change in their equilibrium moisture content directly related to the relative humidity. Inorganic based felts are much better in this regard, the higher the inorganic content, the less the change in dimensions with moisture change. Combination of inorganic and organic fibers to produce felts has been used to some extent in bituminous roofings, and would seem to offer much promise for extended usage.

Felts based upon synthetic organic fibers, if reasonable in cost, largely have had limitations in roofing manufacture because of their inability to withstand the temperatures required in saturation and application of coating asphalts. In the future, they may offer promise as new polymers and possibly manufacturing techniques are developed, or by formulating bituminous products which can be applied at lower temperatures.

However, at present, combinations of the Asplund type of organic fiber with available bituminous saturants and coatings, if properly manufactured and properly applied as roofings, have such a low cost basis in comparison with synthetics, that they would seem to have continuing acceptance as the predominant roofing material.

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Table 1. Shipments of Asphalt and Tar Roofing Products - 1970

Roll Roofings, Sales Square[2]		
Smooth Surfaced		21,670,000
Mineral Surfaced		13,100,000
Saturated Felts		85,000,000 [3]
	Total:	119,770,000
Total Shingles, Sales Square		
Strip		45,490,000
Individual		2,900,000
	Total:	48,390,000

From U. S. Dept. of Commerce, Bureau of the Census, series M29A(70)-13, (1970)

2. The amount which when applied as a roofing will cover 100 square feet of surface.
3. U.S. Department of Commerce data for shipments of saturated felts in 1970 are given as short tons. This value is an area estimate based on the assumption that the shipments were approximate equal amounts of 15 and 30 lb. felts to average 100 sales squares per short ton.

Table 2. Typical Requirements for Asphalt Roof Saturants and Coatings.

Property	Roll Saturant	Shingle Saturant	Coating Asphalt	A.S.T.M. Test Method
Softening Point,(R&B), °F.	100/120	135/150	215/230	E-28
Penetration @ 77°F., 100g/5 sec., $\frac{mm}{10}$	140/200	40/65	16/25	D-5
Flash, C.O.C., °F., min.	550	550	550	D-92
Solubility in CCl_4, %, min.	99.5	99.5	99.5	D-2042
Accelerated Weathering, 51-9 cycle, 0.025" film, hours to spark failure, min.			1500	D-529
Stain No., max.			20	D-1328
Compatibility of coating and saturants, ring in mm., max.	0.5 after 5 hrs. @ 120°F.	0.5,5 hrs. @ 140°F.	0.5, 5 hrs. @ 140°F.	D-1370
Granule stain test			O.K. with specified filler and granule	ARMA[9] 1.1112
Viscosity, Brookfield, No. 2 spindle, 12 rpm @ 400°F., cps, max.			500	

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Abrasion Test and Wear Resistance Of Concrete Terrazzo Flooring Tiles

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The paper summarizes a series of tests, in which the reliability of the Böhme abrasion machine (DIN 52108) in evaluating the wear properties of terrazzo concrete tiles was investigated. In view of the performance of such tiles under service conditions it was concluded that this procedure is not always reliable. It was therefore suggested that the acceptance procedure of such tiles should not be limited to an abrasion test but should also specify a minimum cement content in the terrazzo course. This minimum cement content should be 450 kg. per cu.m while the maximum amount of abrasion should not exceed 1.8 mm.

La communication résume une série d'essais au cours desquels la fiabilité de la machine abrasive de Böhme pour évaluer la susceptibilité à l'usure des dalles de granito a été étudiee. En regard de la performance de ces dalles dans les conditions de service, on en a conclu que la méthode n'est pas toujours digne de confiance. C'est pourquoi il a été suggéré que le processus de réception de ces dalles ne devrait pas se limiter à un essai d'abrasion mais devrait aussi spécifier un pourcentage minimal de ciment dans la couche de granito. Ce pourcentage minimal de ciment devrait être de 450 kg/m^3 alors que le maximum d'abrasion ne devrait pas dépasser 1,8 mm.

Key words: Abrasion test; Böhme machine; concrete terrazzo flooring tiles; DIN 52108; wear resistance.

1. Introduction

It is generally recognized that the use of laboratory tests for predicting the wear properties of flooring materials is a questionable procedure indeed. Generally speaking, in such tests the flooring material is subjected to some kind of abrasion and its wear properties are evaluated accordingly. Unfortunately, it is rather difficult to establish the correlation, if any, between the laboratory abrasion tests and wear properties and it is therefore not surprising that such tests should prove on many occasions to be unreliable means for evaluating wear properties. Nevertheless, probably due to the lack of a better procedure, the abrasion tests are still being used in some countries.

In Israel, the main flooring material is concrete terrazzo tile. The wear properties of these tiles are determined from an abrasion test carried out on a Böhme machine of the type specified in DIN 52108[1][2]. This test will be described later in some detail. However, in line with the preceding discussion, Israeli experience has shown that the amount of abrasion, when determined on the Böhme machine, is also an unreliable parameter for evaluating wear properties. Indeed, it has been demonstrated on many occasions that even tiles which exhibit a low amount of abrasion are liable to rapid deterioration due to wear under service conditions. In practice this implies that the building industry has no adequate means for controlling the quality of the flooring tiles. This undesirable situation resulted on many occasions in unnecessary and unpleasant disputes between owners, contractors and tile manufacturers and emphasized once more the need for a reliable testing procedure. Hence, the present study was carried out in order to establish such a procedure, if possible, by means of the Böhme abrasion test.

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[2] Figures in brackets indicate the literature references at the end of this paper.

As has already been pointed out, the critical aspect in abrasion tests is the correlation between test results and wear properties. This type of correlation, if any, is rather difficult to establish and usually involves prolonged exposure tests which are not easy to assess quantitatively. In order to overcome these difficulties, it was decided to try to relate the amount of abrasion not directly to the wear properties which are difficult to measure, but to some other factors which were proved to determine the wear performance of the tiles and therefore can be assumed to represent this particular property. These factors were the cement content and the quality (hardness) of the aggregate in the terrazzo course. Of course, some other factors (such as production and curing methods) may also affect wear properties. However, as was shown elsewhere [2] (at least under normal local conditions), these factors are negligible compared with the cement content and the quality of the aggregate. Consequently, in the present study an attempt was made to relate the amount of abrasion to the cement content and aggregate hardness only which, in turn, were assumed to represent the wearing quality of the tiles.

2. Experimental Procedure

2.1 Materials

(a) Cement

Ordinary Portland cement complying with Israel Standard Specification IS 1 (virtually coincident with type I of ASTM C150).

(b) Aggregates

Three types of aggregates were used:

- Crushed soft limestone aggregate of white colour, hereinafter referred to as "white" aggregate.

- Crushed limestone aggregate of medium hardness, hereinafter referred to as "yellow" aggregate.

- Crushed hard basalt aggregate of dark colour, hereinafter referred to as "black" aggregate.

Generally speaking, the white aggregate represents a soft material which is not suitable for the manufacture of terrazzo tiles, the yellow aggregate represents the more common types which are normally considered suitable for regular tiles, while the black aggregate is representative of the types suitable for heavy-duty tiles. The physical properties of the three aggregates are summarized in table 1.

The above aggregates were used in three different gradings, namely "coarse" (fineness modulus 5.25 - 5.43), "medium" (fineness modulus 4.70 - 4.76) and "fine" (fineness modulus 3.23 - 3.64). The appropriate grading curves of the aggregates are given in figure 1.

(c) Fillers

The fillers used were crushed stone sand with a fineness modulus in the range of 0.95

to 1.09 (fig. 1). In each mix the sand obtained from the same rock as the aggregate was used.

2.2 Mix Proportions

In all the mixes for the terrazzo course, the cement and filler/aggregate ratio was 1:1 by volume in accordance with local practice. Within this limitation, five mix proportions were studied varying in cement:filler:aggregate ratio from 1:0:1 (mix A) to 1:3:4 (mix E). Accordingly, the cement content in the terrazzo course varied from 260 to 905 kg. per cu.m. The amount of mixing water varied,being determined in each case to give the consistency required for manufacturing the tiles.

Each mix was studied in all gradings in each of the three aggregates, giving a total of 45 mixes. Further details of the mixes are given in table 2.

2.3 Preparation of Test Specimens

Test specimens were 20 x 20 cm tiles, with total final thickness (i.e. after polishing) of approximately 20 mm, the terrazzo course being about 5 mm thick. All specimens were prepared by skilled labor in a tile factory, using the equipment commonly employed in the manufacture of such tiles. Production was strictly standardized and controlled, the only variation in the specimens being the mix used for the terrazzo course (table 2).

The tiles were cast upside down, i.e. the mix for the terrazzo course was placed first and overlaid with the base-course concrete. After leveling, the mold was placed in a hydraulic press and a compacting pressure of 100 kg. per sq. cm applied. The mold was then stripped and the tile placed vertically in a rack. Curing, by complete immersion in water, commenced 16-18 hours after casting and continued for 24 hours. At 7 days, the tiles were polished and stored under laboratory conditions to await testing.

2.4 Testing Procedure

At the age of 28 and 90 days the tiles were subjected to an abrasion test in the Böhme-type machine. In this test two pieces of a tile, 7 cm square, are subjected to abrasion by rotation against a steel plate with emery sand acting as the abrasive agent. The duration of the test, speed and radius of rotation, etc., are standardized and the resistance to abrasion is determined from the reduction in thickness and referred to as the "amount of abrasion". A general view of the testing layout is given in figure 2.

3. Test Data and Their Evaluation

3.1 Influence of Aggregate

The amount of abrasion of the tiles at 28 days is plotted in figure 3 versus three parameters which are commonly assumed to represent hardness of aggregate, namely, (a) the amount of abrasion in accordance with DIN 52108[1], (b) the crushing value in accordance with BS.812[3] and (c) the percentage of wear in accordance with ASTM C131[4].

It can be seen from figure 3 that the amount of tile abrasion is reduced with increase in hardness irrespective of the testing method, the relationship being approximately linear where the crushing value and the percentage of wear are concerned. It can be seen that the grading of the aggregate also affects the amount of abrasion of the tiles, coarser aggregate being associated with lower abrasion and vice versa. Generally speaking, such an effect of the aggregate grading is to be expected in view of the fact that in tile-production the variation in the consistency of the mix must be kept within a narrow range. Hence, the use of coarser aggregate should require less mixing water and improve tile properties as a result of the reduced w/c ratio. However, as it can be seen from table 2, this was not always the case under test conditions and probably some other factors were involved such as the difference in abrasive resistance of the various gradings relative to that of the cement matrix.

3.2 Influence of the Cement Content

The amount of abrasion being dependent on aggregate hardness and grading, the influence of the cement content should be considered accordingly. Consequently, the amount of abrasion is plotted separately (fig. 4) against the cement content for the various aggregates and gradings involved. It can be seen that the resulting relationship is of exponential nature and in fact similar to that usually observed between the w/c ratio and concrete strength. This could have been expected because,owing to the need to use mixes more or less of the same consistency, a higher cement content means a lower w/c ratio and therefore results in a reduced amount of tile abrasion and vice versa. As it can be seen from table 2, this was the case under conditions in hand.

The exponential relation presented in figure 4 implies that, although the amount of tile abrasion is dependent on the cement content, the influence decreases in such a manner that at a certain point a further increase in the cement content would only lead to slight improvement in resistance. This point can be regarded as the optimum cement content or, alternatively, as the maximum practicable amount from both the technological and economic points of view. The relevant optimum values according to aggregate type and grading are given in table 3.

3.3 Discussion and Conclusions

It is quite evident from the presented data that the amount of tile abrasion is closely related to the cement content and hardness of aggregate, i.e. to both factors known to determine the wear properties of the tile. In this respect it can be noted that the amount of abrasion can be reduced either by the use of harder aggregate or a higher cement content, while a tile of good wear properties is characterized by both a relatively high cement content and the use of hard aggregate. Under the conditions in question, it can be seen, for example, that for the basalt (black) aggregate,tile abrasion values as low as 1.4 mm and lower were reached in mixes having a cement content less than 300 kg. per cu.m. However, it has been experienced on many occasions that such a low cement content is not enough to produce tiles of good wear properties. It is therefore evident that the abrasion test is not a suitable means for controlling tile quality,failing to adequately assess the role of the matrix in maintaining the integrity of the tile in service. The problem of matrix quality can be overcome by specifying a minimum cement content in the terrazzo mix. On the other hand, a good quality matrix, resulting from the use of a high cement content, does not yield good wear properties if soft aggregate is used. Consequently, the minimum cement content should be specified together with a maximum value for tile abrasion. At a maximum value of 1.8 mm the use of a soft aggregate (represented here by the "white" variant) will be impossible for any cement content while a minimum cement content of say, 450 kg. per cu.m, will ensure satisfactory wear properties of the matrix.

Summing up, it may be concluded that since the Böhme abrasion test is not always a reliable means for evaluating wear properties of concrete terrazzo tiles, it should be used in conjunction with a requirement for a minimum cement content in the terrazzo course. Accordingly, it is suggested that in acceptance procedure for such tiles the maximum amount of tile abrasion should not exceed 1.8 mm and the minimum cement content should be 450 kg. per cu.m.

4. Acknowledgment

The author wishes to express his sincere gratitude to the Israel Ministry of Housing for providing the grant which made this study possible.

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Table 1. The physical properties of the aggregates.

Property	Unit	Type of Aggregate		
		Black	Yellow	White
Apparent spec.gravity(a)		3.10	2.68	2.60
Absorption(b)	%	0.41	0.75	1.50
Compressive strength(c)	kg/sq.cm	1475	920	650
Crushing value(d)	%	7.6	15.8	19.1
Percentage of wear(e)	%	12.2	22.6	28.4
Amount of abrasion(f)	mm	1.03	1.89	5.00

(a) Determined on 1/4" - 3/8" particles.
(b) Weight percentage after complete immersion of 1/4" - 3/8" particles in water for 48 hours, relative to oven-dry weight.
(c) Determined on 7 cm oven-dry cubes.
(d) Determined on 1/4" - 3/8" particles in accordance with BS.812:1960[3].
(e) Determined on the Los Angeles apparatus, in accordance with ASTM C131-55[4].
(f) Determined on 7 x 7 x 3 cm specimens of rock on the Böhme apparatus in accordance with the DIN 52108[1].

Table 2. Abrasion test data.

Mix Proportions*	Aggreg.	Grading		Materials in kg per cu.m concrete			w/c ratio	Abrasion in mm at (days) **	
		Design.	Fineness Modulus	Cement	Stone sand	Aggregate		28	90
Mixes "A" - 1:0:1	B	Fine	3.64	838		1067	0.44	1.12	1.27
		Medium	4.75	905		1144	0.37	0.99	0.80
		Coarse	5.43	865		1100	0.43	0.90	0.80
	Y	Fine	3.23	852		920	0.42	1.83	1.46
		Medium	4.70	847		957	0.40	1.69	1.33
		Coarse	5.25	838		955	0.46	1.60	1.23
	W	Fine	3.44	847		890	0.44	2.05	1.83
		Medium	4.76	867		954	0.40	2.11	1.78
		Coarse	5.29	854		940	0.39	1.87	--
Mixes "B" - 1:½:1	B	Fine	3.64	517	378	987	0.76	1.41	1.29
		Medium	4.75	571	429	1087	0.55	1.02	0.86
		Coarse	5.43	560	403	1075	0.60	0.88	0.72
	Y	Fine	3.23	550	314	890	0.63	1.98	1.84
		Medium	4.70	575	330	985	0.64	1.92	1.56
		Coarse	5.25	554	340	947	0.62	1.66	1.32
	W	Fine	3.44	553	320	871	0.63	2.52	2.31
		Medium	4.76	577	336	952	0.53	2.30	1.68
		Coarse	5.29	570	334	940	0.59	1.90	--
Mixes "C" - 1:1:2	B	Fine	3.64	385	574	980	0.88	1.89	1.71
		Medium	4.75	415	623	1057	0.70	1.09	0.90
		Coarse	5.43	408	608	1045	0.79	1.06	0.98
	Y	Fine	3.23	411	470	886	0.80	2.61	2.32
		Medium	4.70	424	487	975	0.76	2.46	1.97
		Coarse	5.25	419	483	955	0.83	1.83	1.58
	W	Fine	3.44	412	481	865	0.80	2.98	2.84
		Medium	4.76	424	498	932	0.73	2.89	2.13
		Coarse	5.29	430	502	945	0.76	2.19	--
Mixes "D" -1:1½:2	B	Fine	3.64	296	663	942	1.27	2.10	2.04
		Medium	4.75	328	700	1035	0.92	1.11	1.04
		Coarse	5.43	319	715	1020	1.00	1.27	1.19
	Y	Fine	3.23	325	563	880	1.00	3.01	3.18
		Medium	4.70	336	582	955	0.90	2.75	2.08
		Coarse	5.25	346	597	985	0.90	1.96	1.80
	W	Fine	3.44	325	565	852	1.04	3.70	3.16
		Medium	4.76	335	617	920	0.88	3.42	2.46
		Coarse	5.29	349	612	960	0.93	2.60	--
Mixes "E" - 1:2:3	B	Fine	3.64	246	738	942	1.42	2.54	2.06
		Medium	4.75	273	817	1035	1.00	1.22	1.24
		Coarse	5.43	261	783	1000	1.24	1.34	1.24
	Y	Fine	3.23	269	618	872	1.25	3.29	3.19
		Medium	4.70	287	660	985	0.98	3.06	2.83
		Coarse	5.25	288	662	987	1.06	2.34	2.00
	W	Fine	3.44	269	628	850	1.15	4.16	3.82
		Medium	4.76	286	657	944	1.00	3.60	2.84
		Coarse	5.29	289	674	955	1.04	2.71	--

* Cement: stone sand: aggregate, by volume.

** Average of three tests.

Legend: W = White; Y = Yellow; B = Black.

Table 3. Optimum cement content for the various mixes made with different aggregates.

Grading	Cement content, kg. per cu.m.		
	Black	Yellow	White
Fine	550-600	600-650	600-650
Medium	450-500	550-600	600-650
Coarse	450-500	500-550	550-600

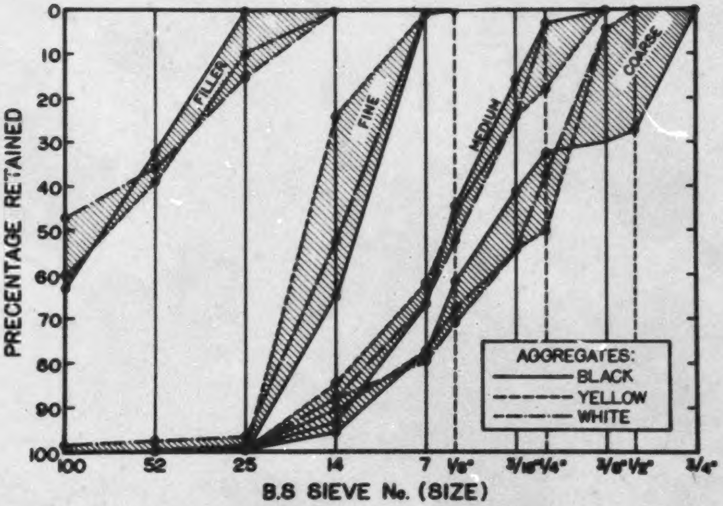


Fig. 1 Grading curves of the aggregates and fillers.

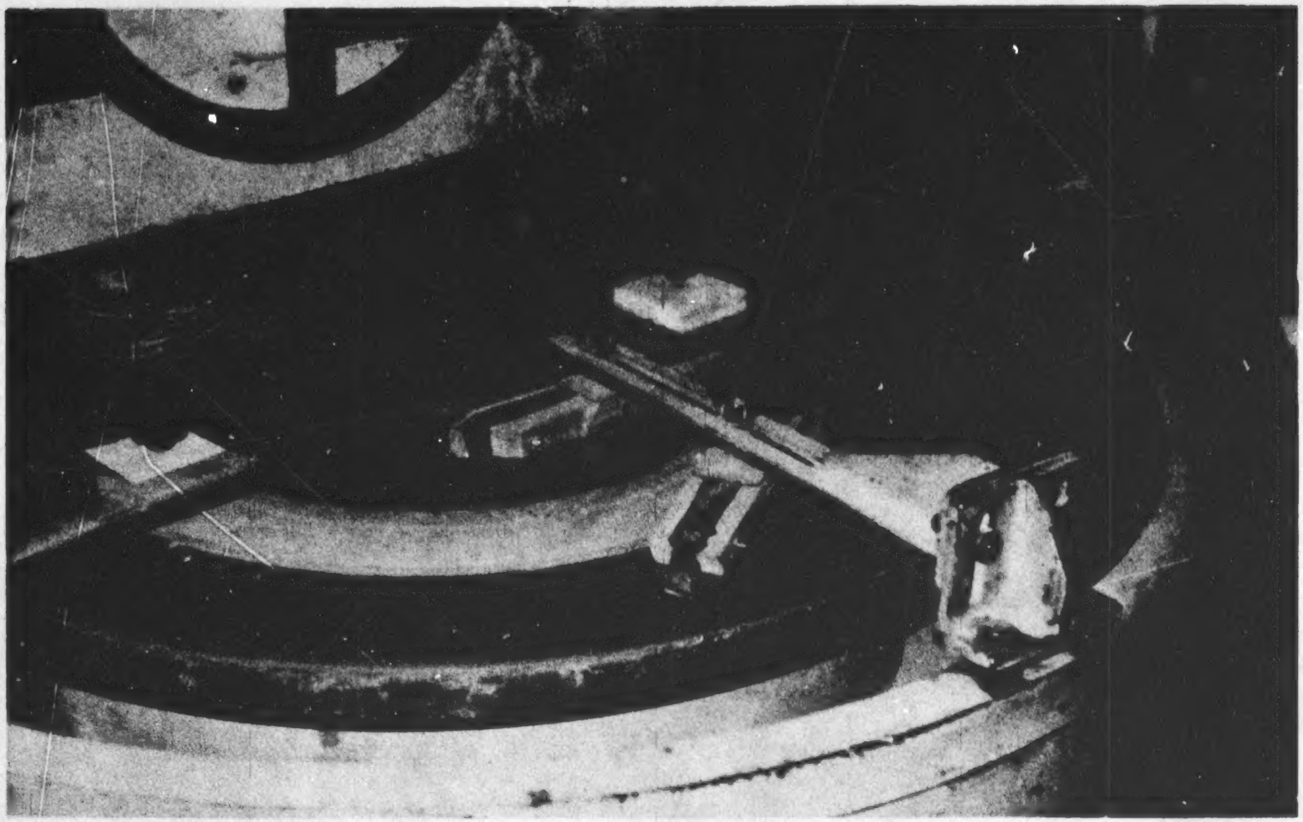


Fig. 2 General view of the abrasion test by means of the Böhme machine.

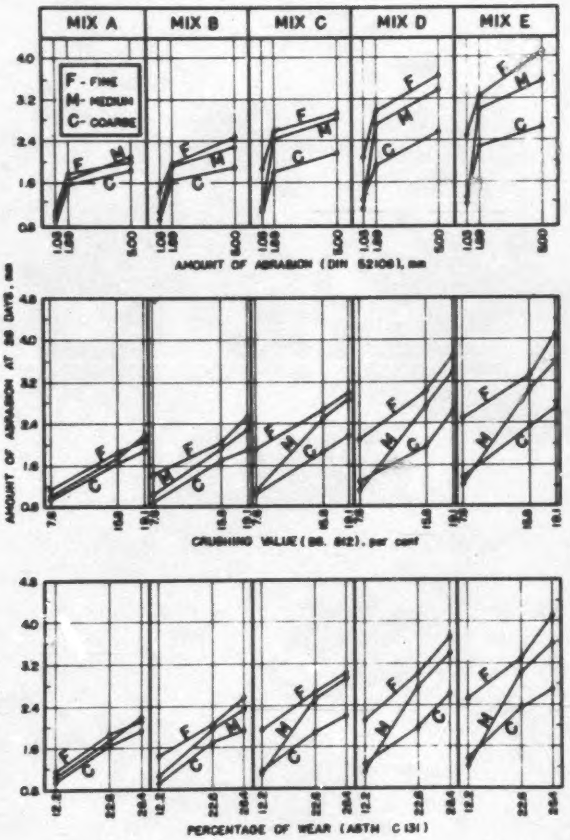
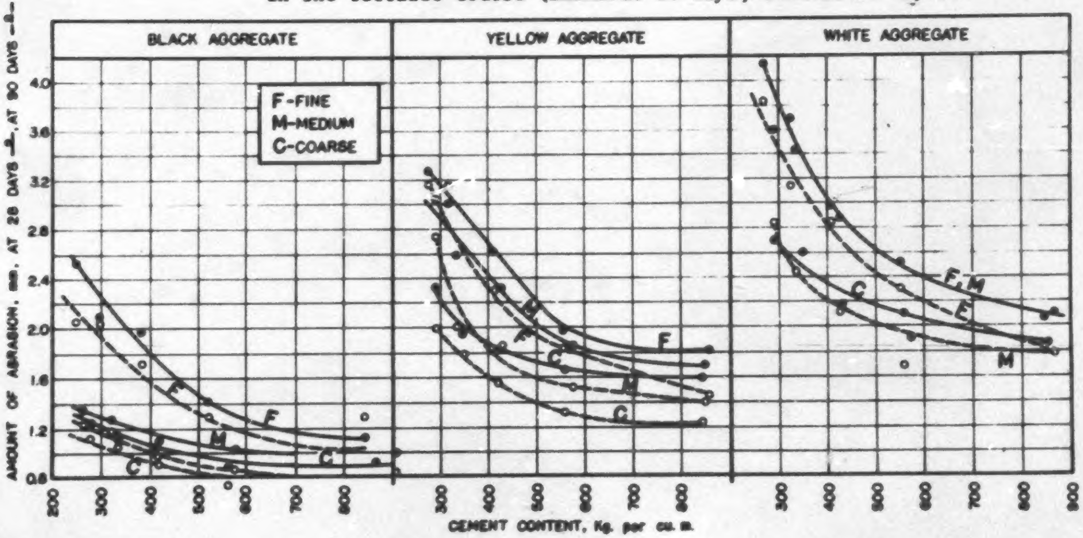


Fig. 3 The effect of aggregate hardness on the amount of abrasion of the tiles.

Fig. 4 The amount of tile abrasion versus the cement content in the terrazzo course (—●— at 28 days; —○— at 90 days).



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Performance Tests for Finish Floors
State-of-the-Art

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The need for performance standards in buildings and in finish flooring is recognized but performance requirements and criteria need to be established. Requirements for finish flooring, based on user needs, were divided into three categories in a symposium at the 72nd Annual ASTM meeting. These were Health and Safety; Comfort, Convenience and Efficiency; and Economics. Criteria are dependent on the art and science of testing.

Sanitation factors, such as cleanability and air pollution are difficult to define. Statistics show a number of deaths and injuries from falls but the number of accidents due to slippery floors is unknown. Fire safety is not discussed as this is outside the scope of our work.

In the second category, resistance to the movement of wheeled vehicles is a problem with carpet but not with other types of finish floors. One question about resilience as related to foot comfort is whether this is related to fatigue or to foot problems. Water and solvent resistance is a problem in certain areas, such as bathrooms, kitchens, and industrial locations. The question of noise or acoustics is outside our scope.

Wear and durability is related to economics as it is a determining factor in life-cost. Since finish flooring is judged on appearance as well as function, it is important to consider change of appearance in wear testing as well as actual loss of material or wearing through.

The state of the art in test development is reviewed and exploratory work at NBS is presented in the areas of cleanability and stain resistance; slip resistance; indentation and resilience; static charge and conductivity; water resistance; and durability or wear.

Le besoin de normes de performance dans les bâtiments et les revêtements de plancher est reconnu,mais les exigences et critères de performance ont besoin d'être établis. Les exigences, fondées sur les besoins de l'usager, pour les revêtements de plancher ont été classées en 3 catégories à un colloque de la 72ème session annuelle de l'ASTM. Elles s'intitulaient Santé et Sécurité; Confort, Convenance et Efficacité; et Economie. Les critères découlent de l'art et de la science de l'essai.

Les facteurs d'hygiène, tels que la capacité de nettoyage et la pollution atmosphérique, sont difficiles à définir. Les statistiques indiquent un certain nombre de morts et de blessures à la suite de chûtes mais le nombre d'accidents provoqués par des planchers glissants est inconnu. La tenue au feu n'est pas discutée car elle est hors du propos de notre travail.

Dans la seconde catégorie, la résistance au mouvement de véhicules à roues est un problème pour les tapis, pas pour d'autres types de revêtement de planchers. La question de l'élasticité en connection avec le confort pour le pied dépend de la fatigue ou de problèmes de pédicure. La résistance à l'eau ou aux solvants est un problème dans certains locaux comme la salle de bain, la cuisine ou les usines. La question du bruit ou de l'acoustique dépasse notre enquête.

L'usage et la durée sont apparentés à l'économie car ce sont des facteurs déterminants dans le coût de vie. Puisque les revêtements de plancher sont jugés aussi bien sur l'apparence qu'en raison de leur fonction, il est important de considérer les changements d'apparence dans les essais d'usure aussi bien que la perte réelle de matériau ou la détérioration totale.

"L'état de l'art" dans le développement des essais est passé en revue et une étude exploratrice du N.B.S. est présentée, relative à la capacité de nettoyage et la résistance aux taches, la glissance, la sensibilité aux marques et l'élasticité, l'électricité statique et la conductibilité, la résistance à l'eau et la durée ou l'usure.

Key words: Carpets; cleanability; conducting; durability; flooring; indentation; resilience; slip resistance; static charge; test methods; water resistance; wear

1. Introduction

In a previous symposium [1][2] I discussed the performance concept in relation to finish floors and described the performance tests being developed at the National Bureau of Standards. The performance concept requires the broader term 'finish floors' as we wish to make distinctions between smooth surface resilient floor coverings and other finish floors, such as carpeting and monolithic surfacings. There has been increasing interest in the performance concept since that symposium and now seems to be an appropriate time to review the state-of-the-art in testing.

In the 1969 symposium [1] I grouped performance requirements for flooring into three categories; health and safety; comfort, convenience and efficiency; and economics. Of the health and safety factors, fire safety and noise reduction are special fields and will not be discussed here. Performance tests will be discussed under six headings related to the three main categories of performance requirements. The first three headings, mainly matters of health and safety, are Cleanability and Stain Resistance; Slip Resistance; and Static Charge and Conductivity. The next two headings, Indentation and Resilience; and Water Resistance, are grouped under Comfort, Convenience and Efficiency. The final heading of Durability or Wear is related to the economics of flooring.

2. State-of-the-Art of Performance Tests

2.1 Cleanability and Stain Resistance

The property of 'cleanability' is the response to overall cleaning, while 'stain resistance' is the response to spills and the spotting necessary to remove spills. Recent studies indicate that carpeting does not increase the bacterial count in hospitals and is therefore safe to use in corridors, patients' rooms, and other areas not required to be aseptic. However, there is some question about whether these studies are completely unbiased. Other studies disagree as to the relative cost of maintenance of carpeting and resilient tile. These studies all indicate the importance of cleanability and the desirability of a test for product evaluation.

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[2] Figures in brackets indicate the literature references at end of this paper

Research on methods for measuring the cleanability, soilability, and stain resistance of smooth surfaces was reported by the National Bureau of Standards [2]. Method 6141 of Federal Test Method Standard No. 141a for washability of paints might be applied to smooth surface floor coverings. However, soiling agents and dyes for evaluating stain resistance would very likely be different for floor coverings, depending on the use-areas under consideration.

Carpet presents a more difficult problem, especially if we wish to compare carpet with smooth surface floor coverings. The surface of carpet is uneven and dirt penetrates through the pile. Methods used for cleaning and spotting carpet are not the same as the cleaning methods used for smooth floors. Standard methods have been developed for carpet soiling by the American Association of Textile Chemists and Colorists (AATCC) and their accelerated soiling method might be used as a basis for development of a test for cleanability. An attempt was made to develop a test method for soilability and cleanability of cotton broadloom rugs by Hensley and Ridgeley of the U. S. Department of Agriculture [3]. They obtained linear correlation between rugs soiled in service and those soiled on a laboratory soiling wheel, using both visual ratings and change in reflectance as criteria. However, changes in reflectance could not be used to measure soiling unless the rugs were undyed, hardly the case in actual service.

Preliminary unpublished work at the National Bureau of Standards indicated that repeated vacuuming does not remove all the dirt within the pile or even on the surface of the carpet. On the other hand, thorough shampooing removes all the dirt. Since degree of soiling depends on the soiling procedure, the conditions of soiling as well as cleaning need to be standardized. These include the time, temperature and humidity at which specimens are conditioned and tested.

There are a number of commercial and trade association methods for spotting and stain removal [4] which might be used as the basis of a standard method for evaluation of carpeting and other floor coverings. It would first be necessary to select standardized stains, representative of what might be encountered in service. Information from private sources [4] suggests that some 150 common stains are encountered in normal service, which illustrates the magnitude of the problem. Development of a standard method for stain removal or spotting will also be difficult due to the great variety of methods presently used.

2.2 Slip Resistance

According to the Final Report of the National Commission on Product Safety [5], falls in the home each year kill about 12,000 and injure an additional 6,900,000 people. The precise causes of the falls are uncertain but slippery floors were listed as one of the possible causes. The same report summarized results of several surveys in which floors and flooring materials were among the leading causes of accidental injuries. Interest in slippery floors as a cause of accidents goes back at least to 1948, when a government survey indicated that a high percentage of injuries in a large government building were due to slipping on floors. This government report led to research on a code for safe walkway surfaces by the National Safety Council and the National Bureau of Standards [6].

An excellent review of test methods for slip resistance of floors, including an analysis of types of devices, was published in 1961 [7]. This review listed the James machine which is the basis of the ASTM D2047-69 method for measuring the static coefficient of friction between sole leather and polish-coated surfaces. The James machine is adapted only for measurement of static friction and is not suitable for field use because of its design. However, a recent study indicates that a static coefficient of friction of 0.5 as measured by the James machine is valid as a measure of safe walkway surfaces [8]. Also mentioned were pendulum type machines, which measure dynamic friction and are adaptable for field measurement. The earliest type was the Sigler machine, developed at the National Bureau of Standards, with which corridor tests reported in 1948 showed good correlation between test results and slip resistance of floors [6]. A modification of the Sigler machine, the British Portable Tester, is applied mostly to roadways but is also used in our laboratories to measure slip resistance of flooring. The British Portable Tester is the basis of the ASTM E303-69 test for measuring surface frictional properties but nothing has been published on testing flooring with this device.

Since the 1961 review was published, the most noteworthy contribution to slip resistance testing has been the Horizontal Pull Slipmeter [9]. This device can be used to measure static friction and also dynamic or kinetic friction if the rate of pull is held constant or controlled within certain defined limits. Robinson and Kopf [10] evaluated this device and found its use valid under laboratory conditions. The machine is small, light, and adaptable for field testing. However, no correlation has been established between service conditions and test results.

Laboratory measurements were performed at the National Bureau of Standards with the British Portable Tester on a variety of floor coverings and monolithic surfacings, using the synthetic rubber slider as in ASTM E303-69 but on both wet and dry surfaces. The results appeared to be meaningful enough to differentiate between floors which are definitely slippery and those which can be considered safe. Field measurements showed that it is possible in some cases to establish whether or not a floor finish is responsible for accidents.

2.3 Static Charge and Conductivity

Static charge is developed on the body of a person by rubbing upholstery or walking on the floor. When the humidity is low, walking on carpet may produce enough voltage to cause sparks and mild electrical shocks. Low humidity is a problem indoors in cold weather. Static charge could be a serious problem in hospital operating rooms and special precautions are taken to avoid sparking when using flammable anesthetics. The resistance of conductive floors and other requirements are prescribed by section 252 of NFPA 56A [11]. However, this is applicable only to smooth flooring.

The problem of evaluating carpet for anti-static property is complicated by the irregular nature of the surface. However, The Carpet and Rug Institute has recently adopted the AATCC method for testing carpet for resistance to static charge [12]. In this method, a test subject walks on a carpet conditioned in a room maintained at 70±2°F. (21.1±1.1°C.) and 20±1 percent relative humidity. The static charge which builds up on the subject while walking is monitored continuously by means of a voltage indicator. Measured voltage during walking and the rate of charge decay when walking is stopped are indications of the "electrostatic propensity" of the carpet. The carpet industry has also experimented with test methods in which a static charge is generated mechanically to eliminate error due to differences between human subjects, and with measurement of "apparent surface resistivity" of carpet [13]. These methods have not yet been perfected.

2.4 Indentation and Resilience

Ability to recover from stress and to absorb energy which might otherwise be transmitted to the body [1, 14] are the aspects of indentation and resilience which are important from the standpoint of flooring performance. Indentation of flooring is usually associated with the unsightly marks produced by furniture legs and stiletto heels. Resilience of floor coverings has been related to foot comfort in studies at the National Bureau of Standards [1, 14, 15] and elsewhere [16].

In their review article Gavan and Wein [15] related indentation and recovery standards in Federal Specifications to degree of cure, implying that these are quality control tests and have no relation to floor damage or to foot comfort. They criticized the McBurney Tester, prescribed in Method 3211, Federal Test Method Standard No. 501a, and recommended the "Armstrong Indentation Machine", as in Method 3221 of the Standard. The authors defined resilience as "a property involving the elastic energy inherent in a material which causes it to regain its original shape when an external load which has been placed on it is withdrawn".

A study by Thorburn [17] indicated that stiletto heel pressures can range from 550 to 1290 psi (3800 x 10^3 to 9000 x 10^3 N/m^2) with some values as high as 2260 psi (15,600 x 10^3 N/m^2). Thorburn proposed a test device called a "Heel Load Simulator", which was criticized by Gavan and Wein [15]. Of course, stiletto heels are not a problem at the present time but styles are unpredictable. According to Boyd [18], heavy furniture may exert a force of 350 pounds (1600N) on one leg or caster. While furniture glides, protectors, and casters are generally designed to prevent excessive concentrated load or pressure on the floor, some casters may concentrate the furniture load over an area of as little as 0.5 square inch (3.2 x 10^{-4} m^2). With a 350-pound (160 Kg) load, this would amount to a pressure of 700 psi (4800 x 10^3 N/m^2). According to Thorburn [17], maximum safe loads for determining the proper size of furniture rests established by industry vary from 25 to 200 psi (172,000 to 1,379,000 N/m^2), depending on the type of floor covering.

In addition to the methods covered by Gavan and Wein [15] and those in Federal Specifications and in Standard No. 501a there are several rebound tests for resilience which might be applied to floor coverings. Resilience is defined as the ratio of rebound height to drop height for a metal plunger in ASTM D2632-67, which provides a method for determining the impact resilience of rubber by measuring vertical rebound. In ASTM D1054-66, impact resilience and penetration of rubber are determined by use of a rebound pendulum. Also, the height of rebound of a steel ball is used to evaluate resilience in sections 95-101 of ASTM D1564-69 for testing slab flexible urethane foam. The rebound method is open to question, however. After all, even fast walking is a slow process and people walking put considerable weight on the heel and then the sole of the foot, so that the foot does not rebound like a ball.

Indentation measurements were performed by the National Bureau of Standards on a variety of floor coverings, using the "Armstrong Indentation Machine" with flat foot indentors, as in Method 3221, Federal Test Method Standard No. 501a. Diameters of the indentors used varied from 0.282 to 1-7/8 inches (0.716 x 10^{-2} to 4.76 x 10^{-2}m) and indentor load was 152 pounds (70 Kg). Initial indentation was roughly proportional to the energies of compression of floor coverings as previously reported, using a load-strain testing machine [1, 14]. This indicates that laboratory measurements of indentation as in the Federal Test Method Standard have some relation to foot comfort. Work by Sigler and Woodward, reported in Building Materials and Structures Report 73 [19] in 1941, was an attempt to relate indentation from furniture glides and also foot comfort to measurements on floor coverings with the "Armstrong Indentation Machine".

2.5 Water Resistance

In wet areas, such as bathrooms and kitchens, it is important to have a floor covering that is resistant to water penetration and retention. It is not only annoying to walk on a damp surface but liquid foods and body wastes are likely to penetrate through a permeable floor covering and create odors and an unsanitary condition. Water penetration has not been considered important because ceramic tile has been used largely in the past for bathrooms and smooth surface resilient floor coverings for kitchens. These products are relatively impermeable to water and almost entirely non-absorbent. Recently, however, carpet has been used extensively in wet areas. Tests at the National Bureau of Standards indicate that carpet is likely to present a problem in such locations. Tests were performed by exposing the faces of carpet squares to water at room temperature. Moisture retention was calculated from increase in weight both immediately and after 24 hours in the conditioned room. Needlepunch outdoor-indoor carpet soaked through immediately and immediately gained about twice its weight in water. Various low-level looped pile carpets, one acrylic with attached sponge rubber cushion, others jute backed wool, acrylic, and nylon, soaked through in 5-10 minutes and gained about 110 percent in weight. About 10-20 percent water was retained after 24 hours in all cases. This indicates that most carpets will appear damp for about a day after a spill and that water will soak through and cause problems. There should be refinement in the test method for water resistance and improvement in carpet intended for wet areas.

2.6 Durability or Wear

In a previous report we defined durability as the time dimension of performance or the time period during which the floor retains its desirable properties [14] Durability includes resistance to wear, impact, light, water, and other deteriorating factors. Wear testing is an evaluative technique designed to determine the deterioration caused by use. Durability tests of finish floors attempt to simulate traffic encountered in service and to measure the deteriorating effects of this traffic. Durability tests are commonly called wear or abrasion tests but mechanical abrasion may be only one factor. For example, traffic tends to cause carpet to become matted due to repeated flexing of the fibers, while the fibers may not be actually abraded or cut and no material loss observed. This is apparent in studying the reference photographs in ASTM D2401-67, Standard Method of Test for SERVICE CHANGE OF APPEARANCE OF PILE FLOOR COVERINGS.

The nature of the abrasion process has been studied for metals [20] and further light on the nature of wear and abrasion might be shed by a study of tribochemistry [21]. Reviews by Wolfe and Cullen [14] and Gavan [22] cover previously reviewed articles. As pointed out by Gavan, wear is a very complex process and wear machines only measure the effects of abrasion which is but one of the factors involved in wear. Burwell [23] defined wear as "the removal of solid material from rubbing surfaces" and he listed the factors involved in wear as follows:

1) Resistance to cutting
2) Resistance to tear
3) Resilience
4) Stress-strain relationships
5) Changes in any of the above by heat, aging, light, moisture, or conditions of stretch or distortion

In view of this, it is not surprising that, as Harper [24] reported, "The fundamental approach to the measurement of wear resistance appears not to have been attempted for flooring materials". Harper further pointed out the problem of the lack of homogeneity of flooring and the statement by Burwell [23] following his work on metals that "there has not as yet been developed any quantitative empirical relation connecting the quantity of wear with the operating parameters such as load, speed, and the material constants". While metals are not homogeneous, they are more nearly so than are flooring materials.

There seems to be a difference of opinion between producers and consumers as to the value of wear tests in specifications. Recent studies indicate the possibility of evaluating flooring by measuring the early stages of wear, which may lead to more meaningful specification tests [26].

Following my suggestions for government-industry cooperation [1], one of the industry members of ASTM Com. F-6 on Resilient Floor Coverings has recently furnished five formulations and corresponding specimens for round robin testing. These flooring products are to be tested using the Taber abraser, which is readily available, relatively inexpensive, and used by most flooring laboratories. Two modifications of the Taber abraser are to be used in the round robin tests. One is the modification described by Frick [25] and the other is the one that I proposed, based on work at the National Bureau of Standards, of using special wheels supplied by a leading manufacturer of abrasives. These wheels are inexpensive enough to be expendable, are less subject to loading than wheels previously used to test flooring, and their vitrified bond eliminates the aging factor. Loss of thickness is used as the wear criterion. Measuring is done in four to eight positions along the periphery, using maximum depth of wear in each position. This is simpler than determining weight loss and more closely related to service. A wide variety of flooring products was tested in our laboratories by this method, including various types of vinyl, asphalt tile, linoleum, printed enamel felt base, monolithic surfacings, quarry tile, and carpet. The results appear promising and in one series, where two different products were compared, statistical analysis showed a significant difference between the wear of two products. Along with round robin laboratory tests, field trials are planned to be performed on at least two of the same products.

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CONVERSION FACTORS FOR UNITS USED

LENGTH	1" = 1 in. = 1 inch = 2.540 cm
	1' = 1 ft. = 1 foot = 30.48 cm
	1 yd. = 1 yard = 0.9144 m
AREA	1 inch^2 = 6.452 cm^2
	1 foot^2 = 0.0929 m^2
	1 acre = 4047 m^2
VOLUME	1 inch^3 = 16.39 cm^3
	1 foot^3 = 0.02832 m^3
	1 gallon (U.S. liquid) = 0.003786 m^3
MASS	1 lb. = 1 pound = 0.4536 kg
MASS/AREA	1 psf = 1 pound/ft.^{2} = 4.882 kg/m^2
FORCE	1 lbf = 0.4536 kgf = 4.448 newton (N)
	1 kp = 1 kgf = 9.807 N
FORCE/AREA	1 dyne/cm^2 = 10^{-5} N/cm^2
	1 psi = 1 lb./in.^{2} = 7.031 kgf/dm^2 = 6895 N/m^2
	1 mm WC (water column)(at 4°C) = 9.806 N/m^2
	1 mm Hg (at°C) = 133.3 N/m^2
VELOCITY	1 mph = 1 mile/hr. = 0 .4470 m/s
TEMPERATURE	$t_c = (t_f - 32)/1.8$
HEAT	1 Btu (International Table) = 1055 joule (J)
	1 Btu/h = 0.2930 watt (W)
	1 Btu/h.ft^2 = 3.152 J/sec. m^2
ILLUMINATION	1 footcandle = 10.76 lumen/m^2 (lm/m^2)
	1 lux = 1 lumen/m^2
	1 footlambert = 3.426 candela/m^2 (cd/m^2)
	1 nit = 1 cd/m^2
REFRIGERATION	1 MBh = 0.293 kW
	1 boiler hp = 9.804 kW
	1 ton = 3517 watt
	1 clo = 0.88 F · ft.^{2} · hr./Btu = 0.155C·m^2/W

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

Volume 1 contains all of the invited papers accepted for the Joint RILEM-ASTM-CIB Symposium on the Performance Concept in Buildings. Opening addresses and reports of the rapporteurs will be included in Volume 2. The Symposium was held in Philadelphia, Pennsylvania on May 2-5, 1972. The subject matter covered in the papers includes physiological, anthropometrical, psychological, sociological, and economic human requirements and methods of evaluation; physical requirements and methods of evaluation in mechanical, acoustical, thermal, dimensional stability, campatibility, fire properties, and geometry areas; operation and maintenance requirements and methods of evaluation in such areas as maintenance, repair, replacement, and versatility; techniques and problems in applying the performance concept to design; and experience gained in application of the performance concept in design building, and building use.

17. KEY WORDS (Alphabetical order, separated by semicolons)
Buildings; components; design procedures; experience in use; materials; performance evaluation; performance requirements; user requirements.

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